Received June 22, 2019, accepted July 9, 2019, date of publication July 17, 2019, date of current version August 7, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2929530

Techno-Economic Analysis and Environmental Impact of Electric Vehicle

A. E. PG ABAS[1], JED YONG[1], T. M. I. MAHLIA[2], AND M. A. HANNAN[3], (Senior Member, IEEE)
[1]Faculty of Integrated Technologies, Universiti Brunei Darussalam, Gadong BE1410, Brunei
[2]School of Information, Systems and Modelling, Faculty of Engineering and Information Technology, University of Technology Sydney, Ultimo, NSW 2007, Australia
[3]Department of Electrical Engineering, Universiti Tenaga Nasional, Selangor 43000, Malaysia

Corresponding author: A. E. Pg Abas (emeroylariffion.abas@ubd.edu.bn)

This work was supported by the University of Technology Sydney under Grant 321740.2232397.

ABSTRACT With the recent emphasis on environmental protection, electric vehicles (EVs) have gained popularity in regions such as Europe, America, China, and Australia; due to their 'zero tail-pipe emission' and low maintenance cost. This paper aims to investigate the feasibility of introducing EVs into the Brunei market using life cycle cost analysis, as well as identify dominant factors that influence its feasibility. Although local data have been used, methodologies adopted in this paper are applicable and directly transferable for analysis of other markets. Our analysis has shown that EV is currently still expensive as compared to the Internal Combustion Engine Vehicles (ICEVs) and Hybrid Electric Vehicles (HEVs) in the market; with its acquisition cost, contributing much to its Life Cycle Cost (LCC). In order to promote EVs and make other types of vehicles less desirable, it is proposed that a direct government subsidy be introduced as well as the current gasoline price to be increased. It has been shown that the initial subsidy of USD$4100 and increasing gasoline price to USD$0.70/litre, would allow EVs to compete comfortably in the market. This subsidy can be gradually reduced with time, as EV becomes cheaper due to the expected reduction in battery price. Environmentally, however, the current greenhouse gas (GHG) emissions from EVs turn out higher than ICEVs, considering the energy chain. In this regard, cleaner renewable energy sources need to be considered and improvement in power plant efficiency needs to be made, to make EVs more environmentally competitive to conventional vehicles. In conclusion, the government needs to look into financial incentives such as subsidy and increasing gasoline price to improve the feasibility of EVs in the market, as well as to improve efficiency of the energy generation and transmission to derive the full benefit of EVs.

INDEX TERMS Techno-economic, life cycle cost, electric vehicle, environmental impact, Brunei.

I. INTRODUCTION

Continuous increase in the world's population has caused an increase in demands for fossil fuel [1], in order to support growing energy needs for social and economic developments. This has resulted in numerous environmental problems associated with burnings of fossil fuel such as pollutions, water contaminations, global warming, etc. With energy demand expected to increase even further [2], the problems are expected to be exacerbated, bringing more environmental headaches. The transportation sector, encompassing land, air and sea transports, represents one of the biggest consumers of fossil fuel, particularly oil [3]; contributing significantly to our environmental problems. A lot of efforts have been made to reduce environmental effect associated with the transportation sector.

References [4]–[7] propose fuel standards and labelling to eliminate inefficient products from the market, to encourage manufacturers to improve efficiencies whilst at the same time, allowing consumers to make informed choices by providing information on prices and efficiencies. It has been argued that fuel standards and labelling for vehicle have the effect of increasing average efficiency of vehicles in the market and consequently reducing the impact of the transportation sector on the environment.

In references [8]–[12], it has been suggested that renewable energies, particularly biofuel, may be adopted to decrease our dependence on fossil fuel as the main supplier of energy as well as to reduce GHG emissions. The International Energy Agency has projected that biofuels may supply up to 27% of

The associate editor coordinating the review of this manuscript and approving it for publication was Vigna K. Ramachandaramurthy.

the world's energy demand for the transportation sector by 2050, reducing CO_2 emissions by around 2.1 *giga-tonnes* per year [13]. This may come in the form of biodiesel [14]; to be used as direct replacement for diesel, and bioethanol [15]; as additive for gasoline to improve its efficiency. However, the use of biofuel is not without its challenges. Depending on the feedstocks being utilised, biofuel production may interfere with human food production and land usage, and furthermore, it has not reached sufficient technological maturity to produce economical and efficient biofuels. This has resulted in, as yet, low adoption of biofuels as alternative energy sources [13].

Another notable effort to reduce environmental effect from the transportation sector is through promotion of Electric Vehicle (EV) [16]–[18]. Although first introduced in the 19th century [19], interest in EVs only started in the 70s, due to high oil prices at the time [20]. However, it was not until the 90s that EVs have really gained popularity due to the introduction of Zero Emission Mandate in US [21]; promoting active researches into different aspects of EVs. Since then, adoption of EVs has been steadily increasing; such that between 2015 and 2016, the number of EVs on the road globally had doubled from 1.26 million in 2015 to 2.52 million in 2016, with US and China at its forefront [22]. This number is expected to grow even further with the expected technological advancement in battery technologies as well as the effect of economies of scale [23].

Numerous authors [24]–[32] have attempted to appraise economic competitiveness of EVs in a market monopolised by conventional Internal Combustion Engine Vehicles (ICEVs). Assessment on the competitiveness of EVs against Hybrid Electric Vehicles (HEVs) and ICEVs, in three developed countries [33] – the UK, the US and Japan – has shown that EV is favourable as compared to both HEV and ICEV in all three countries under consideration in the year 2015. In Europe, however, mixed results have been reported [24]. Life Cycle Cost (LCC) of EV is lower than ICEV in France, Norway and UK, but higher in Italy, Austria, Hungary, Portugal and Germany. The studies have identified strong tax incentive as a determining factor for the competitiveness of EV in some of those countries [33]. Other related studies indicating the feasibility of EV are given in reference [34], in Qatar and reference [35], for EV buses in India.

Mitropoulos et al. [25] focus their study in the US, by comparing LCCs of EV, HEV and ICEV. Based on average prices of vehicles, gasoline and electricity in the US, it has been shown that HEV has the lowest LCC, with EV and ICEV better than one another depending on the assumed distance travelled. The influence of the distance travelled is further highlighted in reference [26], whereby it has been shown that EV becomes more attractive as compared to ICEV and HEV, the higher the distance travelled by the vehicle. However, other than the assumed distance travelled, reference [25] has not analysed variation effect of other variables on LCC of the vehicles. Furthermore, dominant factors that determine LCC of the vehicles have not been identified [26].

The authors in reference [27] have attempted to appraise the competitiveness of EVs against ICEVs and HEVs in the Singaporean market; by considering Singapore's complex tax structure as well as local costs of gasoline and electricity. Maintenance cost, however, has been excluded from the study, making the outcome somehow less reliable. Similar study has been conducted in Australia [28]; highlighting EV's acquisition, electricity and battery replacement costs, as important parameters that determine competitiveness of EVs in the market. However, effect of variations in variables has not been analysed [28]; as different variables affect different types of vehicles differently.

References [27], [28] have concluded that EVs are, as yet, unable to compete against ICEVs, in contrast to references [33]–[35], which have shown otherwise. Other works [24]–[26] have shown that the ability of EV to compete is dependent on many factors such as tax incentive, distance travelled etc.

These, sometimes, mixed results point to the complex interactions between different cost components that determines LCCs of vehicles. Hence, to gauge ability of EVs to compete in a specific market, it is necessary to perform analysis using specific parameters derived from the market or at least, some of the most important parameters. To this effect, this paper attempts to analyse feasibility of EVs in the Bruneian market through LCC analysis; through comparison with existing ICEVs and HEVs. Furthermore, dominant costs associated with LCCs of the different vehicle types as well as the effect of variations of important variables on LCCs of the vehicles are highlighted. Although data parameters are specific for Bruneian market, method used in this paper are applicable and directly transferable for analysing competitiveness of EVs in other markets.

Geographically, Brunei is a small oil-producing country, located in the Southeast Asian region, with a population of around 400,000 people. Brunei market is unique, in the sense that despite its small size and population, the country stands 9th in the world in terms of vehicles per capita; with 99.9% of the vehicles composed of ICEVs [36]. Environmental impact from the road transportation sector accounts for 12.3% of the country's CO_2 equivalent greenhouse gas emission. The government has targeted that by 2025, EVs shall constitute more than 1% of total vehicles on the road, with the proportion growing to 10% by 2035 [37]. LCC analysis of EVs is useful, in this context, to determine focus areas to make the target achievable. Furthermore, environmental impact of EVs is also analysed.

II. METHODOLOGY

A. VEHICLE SELECTION

This study discusses feasibility of EVs in Brunei; through comparison of its LCC as well as environmental impact with currently available HEVs and ICEVs in the market. Mitsubishi i-MiEV has been selected as representative EV. It is compared with Toyota Prius; representing HEV, as well as Toyota Vios and Toyota Corolla Altis; representing ICEVs.

More ICEVs are chosen for this study as 99.9% of vehicles in the country are ICEVs.

i-MiEV is chosen, due to its affordability; as suggested by its Manufacturer Suggested Retail Price (MSRP) in 2017, in comparison to other EVs like Tesla X 90D, BMW i3, etc. [38] Furthermore, i-MiEV was displayed at Brunei Energy EXPO 2011; partly to gauge public's response to EVs, with some success and as such, introduction of i-MiEV in the market is deemed more palatable rather than introducing a totally new and unknown brands.

i-MiEV is compared to similarly-sized sedan cars, Altis, Vios and Prius. Toyota branded vehicles are chosen due to its popularity in Brunei as well as its affordability, where according to the Brunei Automobile Traders Association, Toyota was the best-selling car in 2015. Vios is the most popular model whilst Altis is chosen due to its almost similar selling price (at USD$23,084 without the 20% vehicle import duty tax) to i-MiEV and its similarity, in terms of specifications. Table 1 shows important parameters of the chosen vehicles.

TABLE 1. **Important parameters for the chosen EV, ICEVs and HEV [39].**

Vehicle Names	i-MiEV	Vios	Altis	Prius
Vehicle Type	EV	ICEV	ICEV	HEV
Price (USD$)	22, 995	17, 275	27, 701	23, 561
Curb Wt. (kg)	1168	1090	1290	1420
Torque (Nm)	180	140	173	142 for Engine, 207 for Motor
Engine (cc)	-	1496	1798	1798

B. TECHNO-ECONOMIC ANALYSIS

LCC analysis [40], [41] analyses all associated costs throughout the life of the objects whilst considering time value of money. Within our context, it may be used to evaluate feasibility of EVs from economic perspective, in competing with established HEVs and ICEVs in the market. It also allows identification of high-cost components during life cycle of the vehicle; allowing more focused approaches by manufacturers or authorities to solve feasibility problem. LCC considers all costs related to the whole life cycle of the vehicle [40]- from acquisition to its disposal [42]- and is composed of acquisition, operating, maintenance costs and salvage value. Where applicable, present value calculation is used to calculate LCCs of vehicles [43].

Relationship between current and future values is commonly given as:

$$PV = \frac{FV}{(1+r)^i} \tag{1}$$

And, taking life-time of vehicle as n, Cumulative Present Value (CPV) can be derived [44]:

$$CPV = \sum_{i=1}^{n} \frac{FV_i}{(1+r)^i} \tag{2}$$

As can be seen, PV and CPV are dependent on the assumed interest rate r and year i in which cash flows are expected. Larger r and i give smaller PV and CPV.

1) ACQUISITION COST

Only MSRP [45] is considered under acquisition cost (AC) of i-MiEV, without levying additional import tax. This is because vehicle import tax is usually levied based on engine capacity and hence, current tax rate is not applicable as EV does not run on internal combustion engine. The vehicles are assumed to be purchased through private lump sum payment with no loans taken; freeing acquisition costs from the effect of varying interest rate. Acquisition cost is borne at beginning of the first year only.

Selling prices of EVs are affected by battery price due to their battery sizes. With active research in the area of energy storage, steady decline on the price of battery has been observed and are further expected [23], [46]. It is reported that the cost of battery has been declining annually by approximately 8% between 2007-2014 and is expected to decline further by between 6-9% annually until 2030 [42]. This expected reduction is indeed good news for vehicle manufacturer generally and EV manufacturer specifically; as reduction in battery price is expected to reduce acquisition costs of both EVs and ICEVs, but with more expected reduction for EVs due to their larger battery requirement. Furthermore, it would also affect maintenance cost of the vehicle via reduction in the cost of battery replacements.

2) OPERATING COST

Operating cost (OC) includes fuel costs; either electricity cost for EVs or gasoline cost for ICEVs and HEVs, annual vehicle license fee (VL_i) and annual insurance cover (IC_i) [42].

Fuel costs are dependent on distance travelled as well as vehicles' efficiencies; with fuel cost assumed to be borne at the end of every year. Both ICEVs and HEVs consume gasoline only, with fuel costs ($FC_{ICEV,i}$ and $FC_{HEV,i}$, respectively) given by:

$$FC_{ICEV,i} = \eta_{ICEV} \times D_i \times C_{gas,i} \tag{3}$$

$$FC_{HEV,i} = \eta_{HEV} \times D_i \times C_{gas,i} \tag{4}$$

It is assumed that EV is charged from domestic electric sockets with charging efficiency of η_{ch} [42]. Fuel cost for EV ($FC_{EV,i}$) is given by:

$$FC_{EV,i} = \eta_{EV} \times D_i \times \frac{C_{elec,i}}{\eta_{ch}} \tag{5}$$

where D_i, $C_{gas,i}$ and $C_{elec,i}$ are distance travelled, cost of gas and electricity, respectively.

Generally, VL_i is determined by category of usage and engine displacement, with VL_i for EV assumed to be similar to HEV. On the other hand, IC_i is dependent on cover type and value of vehicle; taken to be third party cover with identical coverage for all vehicles and hence, costing the same amount.

OC can then be represented by:

$$OC = \sum_{i=1}^{n} \frac{FC_i + VL_i + IC_i}{(1+r)^i} \tag{6}$$

3) MAINTENANCE COST

Included in maintenance cost are service and periodic maintenance fee (MF_i), battery replacement (BR_i) and tyre replacement costs (TR_i).

MF_i is calculated based on maintenance rate per distance (MR); obtained from the manufacturer, and incurred at year-end [25]. Unscheduled maintenance is excluded due to inaccuracy and unreliability in getting its estimated value.

$$MF_i = MR \times D_i \tag{7}$$

Battery and tyre costs are incurred in the year in which replacements are made; normally specified by vehicle and tyre manufacturers. As shall be shown, battery replacement is one of the major contributor to maintenance cost for EV. However, with expected decline in battery price [23], [46] comes expected reduction in maintenance cost as well, especially for EVs.

Maintenance cost can then be expressed as:

$$MC = \sum_{i=1}^{n} \frac{MF_i + BR_i + TR_i}{(1+r)^i} \tag{8}$$

4) SALVAGE VALUE

Salvage value (SV) includes scrap values of batteries during replacement and of vehicle at the end of its life. It is taken to be paid at the year in which vehicle or battery is scrapped:

$$SV = \sum_{i=1}^{n} \frac{SB_i}{(1+r)^i} + \frac{SC}{(1+r)^n} \tag{9}$$

where SB_i and SC are the scrap value of battery at year i and scrap value of the vehicle at the end of its lifetime

5) LIFE CYCLE COST CALCULATION

Life Cycle Cost of vehicle is simply the total of present value calculations of acquisition, operating and maintenance costs, less the salvage value. Lower LCC indicates a more affordable vehicle.

$$LCC = AC + \sum_{i=1}^{n} \frac{1}{(1+r)^i} \times \{FC_i + VL_i + IC_i + MF_i + BR_i + TR_i + SB_i\} + \frac{SC}{(1+r)^n} \tag{10}$$

C. SENSITIVITY ANALYSIS

LCC, which forms our basis in determining feasibility of EV in the market, is calculated based on assumptions and projections of some input parameters. For instance, acquisition cost of EV is based on MSRP and may be prone to variations once it enters the market; not least due to expected import tax that may be levied on vehicle. Market uncertainty due to demand and supply, technologies and others, may cause some of these key assumptions to vary, such that it may change LCC of either EV, ICEV or HEV.

Sensitivity analysis is used to assess effect of variations in key assumptions, on LCC calculations of vehicles. Furthermore, it may also highlight parameters that manufacturers may put extra effort in, in order to make EV market competitive in relation to its direct substitutes; ICEVs and HEVs.

Six main input parameters are included in sensitivity analysis; acquisition cost, interest rate, annual distance travelled, costs of electricity and gasoline, and battery prices.

Acquisition cost is the only component that makes up LCC of a vehicle which is not affected by interest rate variations; as such changes in acquisition cost would directly affect LCC. Furthermore, effect of import tax or subsidy may also be analysed by varying acquisition cost; with purchase subsidy commonly required to encourage purchase of relatively new technological product such as EVs. All other costs associated with LCC calculations are influenced by interest rate; with higher interest rate expected to reduce LCC values and vice versa.

LCC calculation is made based on fixed assumption on annual distance travelled D_i, however different drivers are expected to clock different annual mileage; changing maintenance and operating costs of all the vehicles albeit with different amounts. Hence, sensitivity analysis of annual distance travelled shall shed lights on effect of driving patterns on feasibility of EV.

Fuel costs affect operating costs of vehicles; with analysis on variation of both electricity ($C_{elec,i}$) and gasoline ($C_{gas,i}$) prices, particularly interesting due to the subsidised nature of both commodities in Brunei. Variation in gasoline price does not directly affect LCC of EVs, however, it does affect its direct substitutes; ICEVs and HEVs, and shall partly determine ability of EVs to compete. High gasoline price would increase LCCs of ICEVs and HEVs; making EVs more attractive to consumers.

Finally, changes in battery price are expected to not only change battery replacement cost but also acquisition cost of vehicles; as it is expected to change production cost of new vehicles and consequently, their acquisition costs, especially for EVs. Arguably, battery price has been dubbed the most important factor determining feasibility of EVs [23], [29], [46]; with battery price at $USD\$150/kWh$ earmarked as the threshold whereby EVs would become mainstream in US [23] and Europe [23], [47]. As such, sensitivity analysis of battery price provides clearer picture on the extend battery price would have to drop before EVs become feasible in the local market.

D. ENVIRONMENTAL IMPACT ANALYSIS

In this study, environmental impact of EV, in the form of greenhouse gas (GHG) emissions, are measured by considering both its production, operational and end-of-life phases; although emphasise is made on the operational phase as Brunei is primarily a buyer rather than a producer of vehicles.

This is not to say that environmental effects from the production and end-of-life phases are not relevant, but rather the operational phase is emphasised due to its direct contributions to the local environment. Environmental impact of EV is then compared to the impacts of ICEV and HEV, highlighting their differences.

GHG emissions are commonly expressed as Greenhouse Intensity, given in terms of carbon dioxide equivalence. Where required, effects of other non-carbon dioxide greenhouse emissions, particularly methane and nitrous oxide, are converted into their carbon dioxide equivalence, using equation (11), where variable m represents mass of the compounds. The presence of other compounds are omitted from our calculations due to its minimal contribution during the combustion process [48].

$$m_{CO_2,eq.} = m_{CO_2} + 21 \times m_{CH_4} + 310 \times m_{N_2O} \tag{11}$$

Factors 1, 21 and 310 represent Global Warming Potential and signify potential harms caused by CO_2, CH_4 and N_2O in the atmosphere, respectively [48]. Potential harms of one unit of CH_4 and N_2O are equivalent to the potential harm caused by 21 and 310 units of CO_2, respectively.

During the production and end-of-life phases, environmental impact of vehicles (V_{env}) may be approximated by considering environmental effect of its battery (b_{env}) as well as effect of the rest of the vehicle ($body_{env}$), represented as [49]:

$$V_{env} = (m_v - m_b)\, body_{env} + m_b.b_{env} \tag{12}$$

During the operational phase, although EV has zero tailpipe emission, GHG are emitted by power plants during electricity production. Depending on quantity and type of fuel utilised by the power plant, it is important to consider GHG emissions; particularly, carbon dioxide (CO_2), methane (CH_4) and Nitrous oxide (N_20) [50].

(1-η_{tx})% of power produced by the power plant is lost during transmission and distribution [51], where η_{tx} is average efficiency of electrical transmission and distribution system. A further (1-η_{ch})% of power reaching domestic electrical sockets is lost during charging of EV [28]. Given that EV has an efficiency of η_{EV} and it travels D_i km, effective electrical requirement of an EV is

$$E_{pp,EV} = \frac{\eta_{EV} \times D_i}{\eta_{ch} \times \eta_{tx}} \tag{13}$$

As the power plant is producing electricity with efficiency η_{pp} by utilising certain fuel with heating value of HV_{fuel}, the quantity of fuel required by an EV annually is

$$F_{EV} = \frac{E_{pp,EV}}{\eta_{pp} \times HV_{fuel}} \tag{14}$$

For ICEVs and HEV, quantities of fuel required can be easily derived; taking η_{ICEV} and η_{HEV} as efficiency of ICEV and HEV, respectively,

$$F_{ICEV} = \eta_{ICEV} \times D_i \tag{15}$$

$$F_{HEV} = \eta_{HEV} \times D_i \tag{16}$$

From equations (14), (15) and (16), the amount of GHG emitted during the operational phase of ICEVs, HEVs and EVs are derived by considering emission factors of their fuels; gasoline for ICEVs and HEVs, and fuel used by the power plant for EVs.

III. RESULTS AND DISCUSSIONS

Methodologies outlined in the previous section are used to determine the feasibility of EVs in the Bruneian market; using local data obtained from research papers, technical notes and reports from manufacturers and subject-matter experts as well as from the latest market prices obtained from various sources.

A. DATA REQUIREMENT

Economic feasibility of EVs, specifically i-MiEV, is assessed using LCC in equation (10) and compared to that of Vios, Altis and Prius. US dollars (*USD*\$) is used for calculation, with prevailing conversion rate as of 2017 (*USD*\$1 = *BND*\$1.36) used for conversion as required. Effect of currency fluctuations is excluded from our calculations. Interest rate value r is taken to be 5.5%; following local historical interest rate value. **Table 2** shows summary of the important parameters used, with vehicle lifetime of 12 years i.e. n = 12 [52] and annual mileage (D_i) of 14,235 km [53].

Domestic electricity in Brunei is charged according a tiered-tariff system dictated by the government. In this paper, electricity price $C_{elec,i}$ for i-MiEV is taken to be *USD*\$0.0735 (*BND*\$0.10/*kWh*), common tier of average houses in Brunei.

Vehicles considered in this study are classified under private use and hence, annual vehicle license fee is charged at *BND*\$2.25/100*cc or USD*\$1.65/100*cc*; with vehicle license fee for i-MiEV similar to Prius. Third party insurance covers are assumed for every vehicles; costing *BND*\$100 or *USD*\$73.53 annually.

Annual maintenance fee is calculated based on maintenance rate of the different types of vehicles; with maintenance rate set at *USD*\$0.0234/*km*, *USD*\$0.0335/*km* and *USD*\$0.0352/*km* for EV, ICEV and HEV respectively [25]. Maintenance fee of EVs is 30% lower than ICEVs [26]–[28], due to the different mechanical components present in EVs. Tyre replacement cost is charged at a rate of *USD*\$272 or *BND*\$370 [25] for all vehicles, with an average lifetime of 35,000 *km*. Costs of battery replacement are dependent on battery capacity of the vehicles with battery replacement rate of *USD*\$300/*kWh* or *BND*\$407/*kWh*. According to Mitsubishi, warranty for battery pack is 8 *years* or 160,000*km*, however, with $D_i = 14,235$ km, battery needs to be replaced every 8 years [52]. Battery lifetime for HEV is similar to EV but ICEV has a shorter battery life with average battery lifetime of 4 years.

B. TECHNO-ECONOMIC ANALYSIS

Results of calculations are presented in **Table 3** and **Figure 1**; showing LCCs of the vehicles, break-down of their different components as well as percentage of the different components

TABLE 2. Important parameters for calculation [23], [39], [52], [54]–[58].

Input Data		i-MiEV	Vios	Altis	Prius
Vehicles Type		EV	ICEV	ICEV	HEV
Engine-*cc*		-	1496	1798	1798
Battery Size-*kWh*		16	0.42	0.42	1.31
Vehicles Lifetime, *n-years*		12	12	12	12
Acquisition cost	*USD$*	22,995	17,275	27,701	23,561
	BND$	(31, 273)	(23,494)	(37,673)	(32,043)
Vehicle Efficiency, η_{EV}, η_{ICEV} or η_{HEV}-*kWh/km or L/km*		0.185	0.063	0.061	0.039
Annual Distance Travelled, D_i-*km* [53]		14, 235	14, 235	14, 235	14, 235
Fuel Cost, $C_{elec,i}$, $C_{gas,i}$	*USD$/kWh* or *USD$/L*	0.07	0.39	0.39	0.39
	BND$/kWh or *BND$/L*	(0.10)	(0.53)	(0.53)	(0.53)
Charging Efficiency, η_{ch}-*%*		80%	-	-	-
Ann. Vehicle Lic. fee, VL_i	*USD$*	29.75	24.75	29.75	29.75
	BND$	(40.46)	(33.66)	(40.46)	(40.46)
Ann. Ins. Cover, IC_i	*USD$*	73.53	73.53	73.53	73.53
	BND$	(100)	(100)	(100)	(100)
Maintenance Rate, MR_i	*USD$/km*	0.0234	0.0335	0.0335	0.0259
	BND$/km	(0.0319)	(0.0456)	(0.0456)	(0.0352)
Tyre Rep. Cost	*USD$*	273	273	273	273
	BND$	(371)	(371)	(371)	(371)
Tyre Average Lifetime-*km*		35,000	35,000	35,000	35,000
Batt. Rep. rate [23]	*USD$/kWh*	299	299	299	299
	BND$/kWh	(407)	(407)	(407)	(407)
Battery Lifetime-*years*		8	4	4	8
Scrap Val. for batt.	*USD$*	2.21	2.21	2.21	2.21
	BND$	(3)	(3)	(3)	(3)
Scrap Val. for vehicle	*USD$*	22.06	22.06	22.06	22.06
	BND$	(30)	(30)	(30)	(30)

relative to their total LCC. Also shown are cost comparisons of the different vehicles to i-MiEV.

Our results indicate that LCC of i-MiEV (EV) is *USD*$32,902.29 over its 12 years lifetime, clearly above LCCs of both Vios (ICEV) at *USD*$26,425.51 and Prius (HEV) at *USD*$30,687.50. It is, however, less than Altis (ICEV) at *USD*$36,801.05. As such, feasibility of EV relative to other vehicles are dependent on the vehicles considered; especially when comparing against ICEVs which literally have thousands of possible models to choose from, with different performances and prices. Furthermore, different local parameters, for instance tax structures and fuel prices would affect the feasibility of EVs to compete against other types of vehicles. Indeed, results from studies have shown mixed conclusions, with some concluding that LCC of EV [33]–[35] as the lowest, and yet another [25]–[28] concluding that EV is as yet unable to compete with other types of vehicles.

TABLE 3. Calculations results for the different vehicles.

Vehicles		i-MiEV	Vios	Altis	Prius
Life Cycle Cost – *LCC*	*USD$*	32, 902.29	26, 425.51	36, 801.05	30,687.50
	%age LCC	100	100	100	100
	Comp to EV, *USD$*	0	-6, 476.78	+3, 898.76	-2, 214.79
Acq. Cost - *AC*	*USD$*	22, 995.00	17, 275.00	27, 700.74	23, 561.31
	%age LCC	69.89%	65.37%	75.27%	76.78%
	Comp to EV, *USD$*	0	-5, 720.00	+4,705.74	+566.31
Operating Cost–*OC*	*USD$*	3, 025.13	3, 905.70	3, 855.50	2, 803.66
	%age LCC	9.19%	14.78%	10.48%	9.14%
	Comp to EV, *USD$*	0	+880.57	+830.37	-221.47
Main. Cost – *MC*	*USD$*	6, 896.36	5, 260.79	5, 260.79	4, 336.73
	%age LCC	20.96%	19.91%	14.30%	14.13%
	Comp to EV, *USD$*	0	-1, 635.56	-1, 635.56	-2, 559.63
Salvage Value – *SV*	*USD$*	-14.20	-15.98	-15.98	-14.20
	%age LCC	-0.04%	-0.06%	-0.04%	-0.05%
	Comp to EV, USD$	0	-1.78	-1.78	0

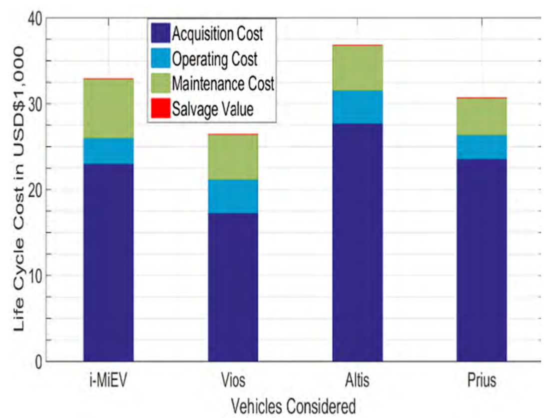


FIGURE 1. LCC of the different vehicles; differentiating their acquisition, operating, maintenance and salvage costs.

It is important, however, to identify the dominant factors that influence the feasibility of EV in a particular market.

As can be seen from **Table 3** and **Figure 1**, LCCs of all vehicles are dominated by acquisitions costs; constituting 69.89%, 65.37%, 75.27% and 76.78% of their LCCs for i-MiEV, Vios, Altis and Prius, respectively. Acquisition costs represent the initial costs incurred and are not affected by interest rate. It is followed by maintenance costs and then, operating costs.

Comparing LCC of i-MiEV with the two (2) ICEVs; Vios and Altis, shows that LCC of i-MiEV is *USD*\$6,476.78 more than Vios but *USD*\$3,898.76 less than Altis. This is mostly due to differences in their acquisition costs; with i-MiEV *USD*\$5,720.00 more expensive than Vios but *USD*\$4,705.74 cheaper than Altis. It is worth highlighting that the acquisition cost of i-MiEV in **Table 1** excludes import tax which is normally levied on imported vehicles. Charging i-MiEV the 15% import tax would raise its LCC to be only *USD*\$450 cheaper than Altis.

Maintenance costs are the second most dominant contributor to LCCs of the vehicles. Maintenance cost of i-MiEV is noticeably higher than both ICEVs due to its higher battery capacity necessitating higher battery replacement cost. i-MiEV requires $16kWh$ battery to operate and with an assumed battery replacement rate of *USD\$*299/*kWh*, this equates to an un-discounted value of *USD*\$4,788.24. This is in contrast to the un-discounted cost of each battery replacement for ICEVs of only *USD*\$125.69; representing only 2.62% of the battery replacement cost for i-MiEV. Granted, i-MiEV requires less regular battery replacement; only once over its entire lifetime, and also has a 30% lower maintenance rate than both ICEVs. However, the exorbitant cost of that one battery replacement far engulfs the effect of longer battery lifetime and lower maintenance rate.

Comparing i-MiEV with Prius shows that i-MiEV has higher LCC than Prius, with a difference of *USD*\$2,214.79. With almost similar acquisition costs of approximately *USD*\$23,000, the difference in their LCCs can be mostly attributed to the higher maintenance cost of i-MiEV. Again, battery replacement cost plays a big role. Although Prius also uses electricity, it primarily runs on gasoline. It has battery packs; charged during normal running of the vehicle, and the stored electricity is used to only assist the vehicle at low speed. Hence, battery requirement of Prius is much less; requiring only $1.31kWh$ of battery capacity in contrast to the $16kWh$ for i-MiEV. Consequently, the un-discounted battery replacement cost for Prius is less at *USD*\$392.04; more than the *USD*\$125.69 cost for ICEVs but still, a small fraction of the *USD*\$4, 788.24 battery replacement cost for i-MiEV. It is noted that the battery lifetime for Prius is similar to i-MiEV at 8 years, but its maintenance rate of *USD*\$0.0259 is approximately 11% more than the maintenance rate for i-MiEV at *USD*\$0.0234.

i-MiEV has 22-23% lower operating cost than both ICEVs; attributed mostly to lower fuel costs of i-MiEV, costing *USD*\$0.017/*km* to run compared to *USD*\$0.025/*km* and *USD*\$0.024/*km* for Vios and Altis, respectively. However, it is noted that operating costs only represent between 9-15% of the LCCs of the vehicles. This is due to the subsidised nature of both electricity and gasoline; considerably lowering the fuel costs and hence, the operating costs of the vehicles.

Prius, on the other hand, has a lower operating cost than i-MiEV. Although Prius primarily uses gasoline, it also uses stored electricity; charged during normal running of the vehicle, and hence, is relatively more efficient than both ICEVs, at $0.039L/km$. At the subsidised gasoline price of *USD*\$0.39/*L*, this equates to *USD*\$0.015/*km*; slightly less than fuel cost of i-MiEV at *USD*\$0.017/*km*, which explains the slightly higher operating cost of i-MiEV.

Salvage values are only able to recoup small amount, due to the meagre amount offered for scrapped batteries and vehicles.

Looking at cost breakdown of i-MiEV, acquisition cost contributes the most to its LCC; with a percentage of around 70%, similar to other studies [26], [34]. In fact, it has been reported [26], [34] that the high acquisition cost of EV far outweighed the benefit of fuel savings from using EV. The acquisition cost is followed by maintenance cost at 21%; 45% of which is attributed to its battery replacement cost [27], [28]. In fact, battery replacement represents 9.5% of the overall LCC of i-MiEV, a big portion considering that its battery is replaced only once during its lifetime. Maintenance cost exceeds operating cost of the vehicle. Operating cost represents only around 9% of LCC; the low cost due to the subsidised electricity price. During the 12 years' lifetime of i-MiEV, sale of scrapped battery and vehicle, claw back a meagre 0.04% of its LCC.

C. SENSITIVITY ANALYSIS

Sensitivity analysis is then performed to investigate effect of varying some input parameters. Six parameters are chosen for the analysis; acquisition cost (AC), interest rate/discount rate (r), annual distance travelled (D_i), electricity ($C_{elec,i}$) and gasoline price ($C_{gas,i}$), and battery price. Varying acquisition cost of i-MiEV and electricity price affect LCC of i-MiEV only, whilst varying gasoline price affects LCC of Vios, Altis and Prius. On the other hand, varying battery price affects all vehicles types, albeit with different proportion.

Acquisition cost is the most dominant cost associated with LCC of i-MiEV and the effect of changing acquisition cost on the LCC of i-MiEV is shown in **Figure 2**. Reduction in acquisition cost may result from reduction of selling price from manufacturer or through subsidy by government to encourage adoption of EVs in the market [24], [26]. Conversely, tax may be imposed, effectively raising acquisition cost.

It can be seen that acquisition cost of i-MiEV would need to drop by approximately 28% and 10%; or corresponding reductions of approximately *USD*\$6, 478 and *USD*\$2, 219, to compete with Vios and Prius, respectively. However, as i-MiEV is already over 15% cheaper than Altis; with Vios's price tag of *USD*\$22, 995.00 as compared to *USD*\$27, 700.74 for Altis, acquisition cost of i-MiEV may be increased by a further 16%-17% and yet, still remains competitive to Altis. As has been discussed, acquisition cost of i-MiEV excludes import tax. Imposing the lowest import tax rate of 15%; effectively raising acquisition cost by 15%, would make LCC of i-MiEV to be slightly less than Altis by just *USD*\$450.

Effect of varying interest rate value r on life-cycle costs of vehicles is shown in **Figure 3**; with r varied between 0%-10%. Generally, LCCs decrease with an increase

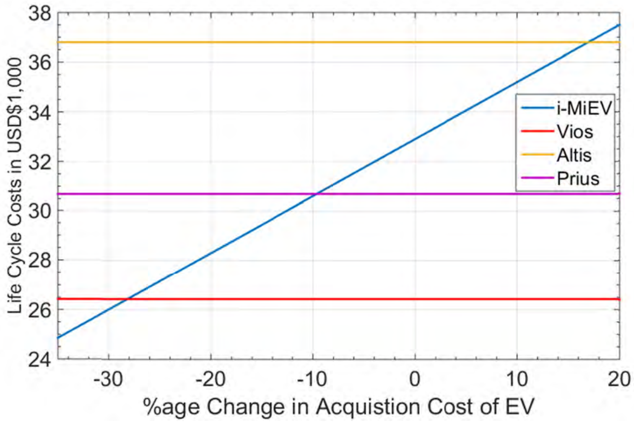


FIGURE 2. Effect of changing acquisition cost of i-MiEV on its LCC, as compared to LCC of Vios, Altis and Prius.

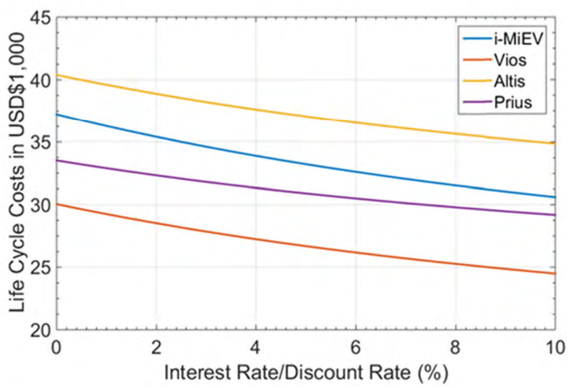


FIGURE 3. Effect of Interest Rate value on the LCC of the vehicles.

in interest rate; with higher rate making future expected costs such as operating and maintenance costs much less than their undiscounted values.

Curves for Altis and Prius are flatter than curves for i-MiEV and Vios, indicating that LCCs of Altis and Prius are less affected by changes in interest rate. This is because acquisition cost, which is not affected by interest rate, contributes larger portion to LCCs of both Altis and Prius; 75% and 77% respectively. On the other hand, operating and maintenance costs contribute 30% and 35% to LCCs of i-MiEV and Vios, respectively. Operating and maintenance costs are incurred future values and hence, discounted values of both operating and maintenance costs are less with increasing interest rate; resulting in steeper curves.

Figure 4 shows the effect of changing annual distance travelled on the LCCs. Increasing distance travelled necessitates increase in fuel consumptions and maintenance cost. Furthermore, tyres and battery are expected to be replaced more regularly; increasing maintenance cost even further. These increases result in general increase in LCCs of vehicles as shown in the figure. At 14,235 km, the difference between LCCs of i-MiEV and Vios is $USD\$6,476.78$, with the difference reducing to $USD\$5,601.61$ at 20,000 km. This is

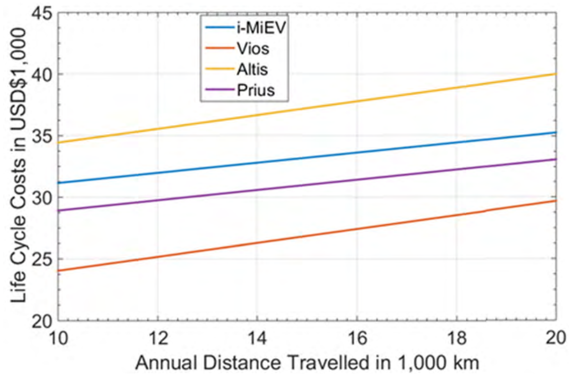


FIGURE 4. Effect of Annual Distance Travelled on LCC of the vehicles.

due to the effect of higher fuel and maintenance costs of Vios as compared to i-MiEV. Increase in the differences between LCCs of i-MiEV and Altis at longer distance travelled, may be similarly attributed to the effect of higher fuel and maintenance costs of Altis as compared to i-MiEV. Although i-MiEV is more fuel efficient than Vios, annual distance travelled would need to be increased to a much higher value for it to overcome the high acquisition cost of i-MiEV. Extrapolating, distance travelled would need to be increased to approximately 57,000km per year for LCCs of i-MiEV and Vios to be the equivalent. This is in contrast to the 9,100km/yr and 60,000km/yr distance travelled reported in references [25], [26], respectively, for LCCs of EV and ICEV to be at parity; highlighting the importance of using local data to evaluate feasibility of EV in a given market. The stark contrast is due to subsidised nature of both electricity and gasoline in Brunei; putting more emphasis on upfront acquisition cost rather than operating cost in determining LCC of vehicles.

Next, analysis on the effect of reducing battery price on LCCs is performed and shown in **Figure 5**. Reduction in battery price leads to reduction in both acquisition and battery replacement cost of vehicles. Overall, these lead to reduction in LCCs of all vehicles as shown in **Figure 5**. As can be seen, LCC of i-MiEV reduces steeply with reduction in battery price. The larger battery capacity of i-MiEV over other vehicles leads to a greater reduction in acquisition and battery replacement costs, as generally, batteries are priced according to its capacity. LCC of i-MiEV is less than Prius after *30%* reduction in battery price. However, only by an 86% reduction in battery price from its current value of $USD\$299/kWh$ to $USD\$41.90$, would i-MiEV become cheaper than Vios. At the predicted battery price of $USD147/kWh$; where EVs are expected to be mainstream [23], [47], LCC of i-MiEV is lower than Altis and Prius, but still remains higher than Vios.

Relationship between LCCs of the vehicles to varying electricity and gasoline prices, is depicted in **Figure 6**. It can be clearly seen that as electricity price is increased, LCC of i-MiEV also increases whilst LCCs of Vios, Altis and Prius remain constant. But as gasoline price is increased, LCCs of

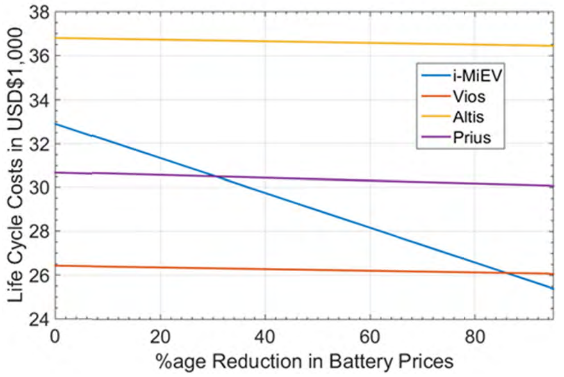


FIGURE 5. Effect of reduction in battery prices on life-cycle costs of the vehicles.

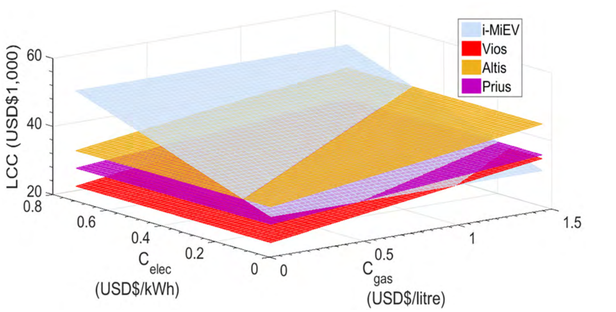


FIGURE 6. Relationship between LCCs of the vehicles with electricity and Gasoline costs; showing i-MiEV has lower LCC at certain electricity and gasoline prices.

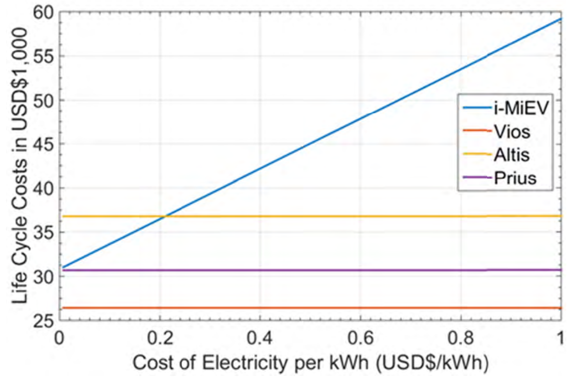


FIGURE 7. Life-cycle costs of the vehicles against Cost of Electricity with cost of gasoline fixed at *USD*$0.3897/*litre* (*BND*$0.53/*litre*).

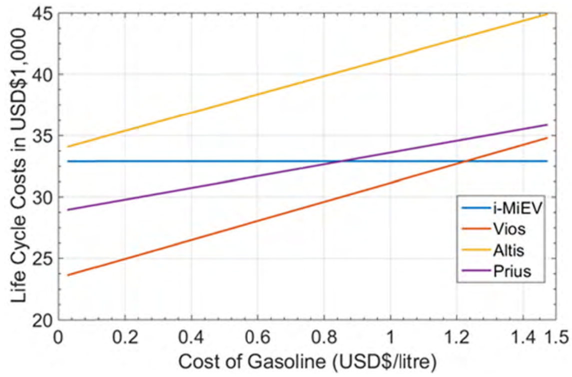


FIGURE 8. Life cycle costs of the vehicles against Cost of Gasoline with the cost of electricity fixed at *USD*$0.0735/*kWh* (*BND*$0.10/*kWh*).

Vios, Altis and Prius increase whilst LCC of i-MiEV remains constant. These are due to their different fuel requirements.

It is observed that for every electricity price, there exists a corresponding gasoline price that would make LCC of i-MiEV to be at parity to LCCs of the other vehicles. Gasoline price below this value, would make i-MiEV to be more expensive as compared to the particular vehicle and gasoline price above this value would make i-MiEV to be cheaper. Similarly, it can be said that for every gasoline price, there exists a corresponding electricity price that would make LCC of i-MiEV to be at parity with LCCs of the other vehicles. Thus, electricity and gasoline prices play important roles in determining feasibility of EVs. Since both resources are controlled and subsidised by the government, these can be used by policy makers to promote EVs in the Bruneian market; either by manipulating selling price of one or both of the resources.

The effect of changing price of one of these resources whilst keeping the other at the current subsidised costs, may be analysed by dissecting the 3D plot in **Figure 6** at subsidised gasoline price of $USD\$0.3897/litre$ ($BND\$0.53/litre$) and subsidised electricity price of $USD\$0.0735/kWh$ ($BND\$0.10/kWh$), to produce **Figure 7** and **Figure 8**, respectively.

Effect of varying gasolines on LCCs, whilst fixing electricity price at $USD\$0.0735/kWh$ is given in **Figure 8**. Reducing gasoline price even further from current price of $USD\$0.3897/litre$ results in expected reduction in the LCCs of Vios, Prius and Altis; making differences in the LCCs of i-MiEV to both Vios and Prius, even larger. It is highlighted that the LCC of Altis remains higher than i-MiEV even with the cost of gasoline reaching as low as $USD\$0.01/litre$. This is the consequence of the high acquisition cost of Altis. Conversely, increasing the gasoline price, increases LCCs of Vios, Prius and Altis. Gasoline prices at approximately $USD\$0.85/litre$ and $USD\$1.24/litre$ result in the LCCs of Prius and Vios, respectively, to be at par with the LCC of i-MiEV.

Generally, the higher the electricity price, the higher the gasoline price needs to be, for i-MiEV to be able to compete with other vehicles. **Figure 9** may be used by policy makers to simultaneously set prices of both, electricity and gasoline in the market; by decisively removing some of their subsidies or through taxation. Of course, this very much depends on the policy of the government. As it stands; with current electricity and gasoline prices of $USD\$0.0735/kWh$ ($BND\$0.10/kWh$) and $USD\$0.390/litre$ ($BND\$0.53/litre$), respectively, i-MiEV is able to compete only with Altis, but not with Vios and Prius. To encourage adoption of EVs, electricity prices needs to be reduced whilst increasing

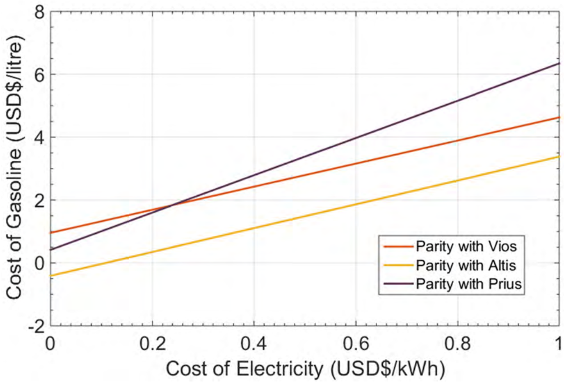


FIGURE 9. Relationship between costs of electricity and gasoline to achieve parity in terms of LCC, between i-MiEV and the different vehicles.

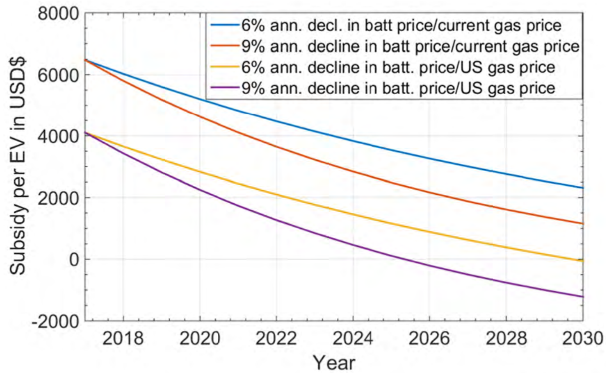


FIGURE 10. The amount of subsidy required for i-MiEV to be at least at a par or cheaper than other vehicles between 2017 and 2030; with cost of gasoline at *US*\$0.3897/*litre* and *US*\$0.6966/*litre*.

gasoline prices. Admittedly, electricity price in Brunei is already one of the cheapest [59] in the world and it may not be feasible to reduce it even further. As such, increasing gasoline price may be more realistic if the government wants to promote EVs. At current electricity price of *USD*\$0.0735/*kWh*, gasoline price would need to be raised by nearly 220%, above *USD*\$1.24/*litre*; higher than US gasoline price at *US*\$0.6966/*litre* but still below the price of the most expensive gasoline in the world at *USD*\$2.12/*litre* in Hong Kong [60]. Indeed, correlation between gasoline price and EV adoption has been reported in reference [61].

To promote EVs, the government needs to look into incentives to reduce acquisition cost of EV, which contributes the most to its LCC. Studies at different localities [24], [33] have shown that strong incentive from governments, in the form of direct subsidy, is needed in order to promote the use of EV. In the case of Brunei, initial subsidy of *USD*\$6, 500 would suffice to allow EVs to compete with other ICEVs in the market. This is indeed good news as it is expected that battery price shall decline between 6-9% annually until 2030; allowing government to gradually reduce its subsidy whilst continuously encouraging the use of EVs. After 2030, battery price is expected to be stable [23]. Similarly, EV manufacturers need to concentrate their effort on reducing acquisition cost to make EV more competitive. As the subsidised electricity price in Brunei is already very cheap, improving fuel efficiency would not be as effective in reducing LCC of EVs as it is for countries with expensive electricity prices.

Figure 10 shows the subsidy required for i-MiEV to be at least at a par or cheaper than Vios, Prius and HEV between 2017 and 2030; with current local gasoline price and gasoline price set at the current US price. At current local gasoline price, it can be seen that the subsidy amount to encourage purchase of one unit of i-MiEV decreases with time as battery price reduces annually; with the amount decreasing faster with a 9% decline in battery price. In 2017, the subsidy amount is *USD*\$6476.78 per unit of i-MiEV, with the amount dropping to *USD*\$2313.73 and *USD*\$1154.50 per unit of i-MiEV in 2030 with 6% and 9% reduction in battery price, respectively. It is noted that in 2030 when battery price is expected to be stable, even with 9% annual reduction in battery price from 2017-2030; a cumulative reduction of more than 30% of its current price, subsidy would still need to be provided for i-MiEV to compete with Vios.

It is noted that at current US gasoline price of *USD*\$0.6966/*litre* [60], LCC of i-MiEV is still higher than that of both Prius and Vios.

As has been previously discussed, both electricity and gasoline prices may be varied to encourage EVs in the market. **Figure 9** shows relationship between electricity and gasoline prices for i-MiEV against other vehicles; with values on the lines indicating electricity and gasoline prices where LCC of i-MiEV is equal to LCCs of the respective vehicles. For a given electricity price, gasoline price above a given line would make i-MiEV more attractive. For instance, for a given fixed electricity price of *USD*\$0.0882/*kWh*, gasoline price would need to rise above *USD*\$0.9398/*litre* and *USD*\$1.2817/*litre* for i-MiEV to compete with Prius and Vios, respectively. However, at that electricity price, Altis turns out to be more expensive than i-MiEV irrespective of gasoline price. Similarly, it can be said that for an assumed fixed gasoline price of *USD*\$2.00/*litre*, electricity may be sold up to *USD*\$0.267/*kWh*, *USD*\$0.283/*kWh* and *USD*\$0.636/*kWh*, and i-MiEV would still be competitive with Vios, Prius and Altis, respectively.

To allow i-MiEV to compete with other vehicles, at least until 2030, when battery price is expected to be stable, the government may need to consider increasing gasoline price to discourage purchase of ICEVs, on top of the subsidy to help with upfront cost of acquiring EVs. The amount of subsidy required for i-MiEV to be at least at a par or cheaper than Vios, Prius and HEV, with gasoline price increased to *US*\$0.6966/*litre* (current gasoline price in US), is shown in **Figure 10**. This represents an increase of 78.8% from the current local gasoline price. The amount of subsidy can be gradually reduced with time, with the decrease in subsidy naturally steeper with higher annual decline in battery price. In the end of 2017, the amount of subsidy required is *USD*\$4103.25; 37% less than the subsidy required with normal gasoline price. This is because higher gasoline price increases LCCs of the other vehicles; albeit still not sufficient to compensate for the high acquisition cost of EVs, and hence, still requiring government subsidy. No government subsidy is required in 2030 as battery price is expected to stabilise, and the LCC of i-MiEV at the expected battery price in 2030, actually turns out cheaper than the LCCs of other vehicles considered in this study.

D. ENVIRONMENTAL IMPACT ANALYSIS

Analysis on the potential environmental impact of EVs are performed; concentrating more on operational phase of the vehicles and using emission data from i-MiEV, Vios, Altis and Prius. Particularly, emissions of these vehicles shall be compared, considering local energy source which utilise mostly natural gas. Other than parameters in **Table 2**, parameters in **Tables 4** and **5** [62] are also used. **Table 4** gives parameters required to determine environmental impact during production and end-of-life phases, whilst **Table 5** gives parameters required for operational phase. Efficiency of power plant η_{pp} and average efficiency of transmission η_{tx} are taken to be 28.4% [63] and 93.586% [64], respectively. It is noted from **Table 4** that the end-of-life phase produces minimal GHG emission as compared to the production phase.

TABLE 4. Emissions during production and end-of-life phase, per kg of mass.

Phases	Production		End-of-life	Total
	Extraction	Manufacturing		
body$_{env}$ (kg)	1.930	1.228	0.014	3.172

TABLE 5. Greenhouse gases combustion of natural gas and motor gasoline [62].

Fuel Type and unit	Heating value (kWh per unit)	kg CO_2 per unit	g CH_4 per unit	g N_2O per unit	kg CO_2 equiv. per kWh
Natural Gas (*scf*)	*0.30092295*	*0.05444*	*0.00103*	*0.0001*	*0.181084992*
Motor Gasoline (*litre*)	*9.685114224*	*2.31943016*	*0.10038536*	*0.02113376*	*0.240378137*

Equations (11)-(16) are used to calculate greenhouse intensity of the different vehicles. **Figure 11** shows GHG emission during production, operational and end-of-life phases. It can be seen that i-MiEV produces the highest emission over its lifetime, followed by Altis, Prius and Vios. The high GHG emission of i-MiEV is mainly attributed to emission from the production of the large Li-ion battery; with one replacement over its lifetime.

Table 6 depicts GHG emission of the different vehicles by considering their operational phase only. Prius produces the least amount of GHG; with an emission of 1292.47 *$kgCO_2$ equiv.* annually or 0.091 *$kgCO_2$ equiv.* per unit distance travelled annually. This is followed by Altis and Vios; emitting 2021.56 *$kgCO_2$ equiv.* and 2087.84 *$kgCO_2$ equiv.* annually, respectively. i-MiEV performs the worst, emitting 2021.56 *$kgCO_2$ equiv.* annually.

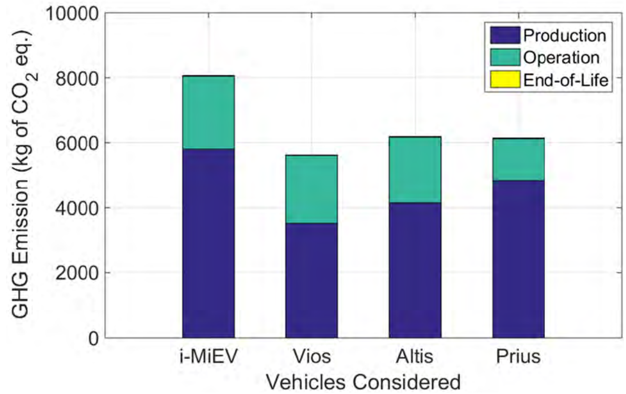


FIGURE 11. Emissions of different Vehicles, at different phases.

TABLE 6. Calculations of greenhouse gases for the different vehicles during operational phase.

	i-MiEV	Vios	Altis	Prius
Fuel Consumption per year (*scf* or *litre*)	*41 158 scf of natural gas*	*897 litres of gasoline*	*868 litres of gasoline*	*551 litres of gasoline*
Total CO_2 equiv. per year (*$kgCO_2$ equiv. /yr.*)	*2242.809804*	*2087.8425*	*2021.561785*	*1292.473928*
CO_2 equiv. per year per dist. (*$kgCO_2$ equiv. /(yr.km)*)	*0.15755601*	*0.146669652*	*0.142013473*	*0.090795499*

These results are very surprising indeed, as EVs have been touted as a form of clean technology. This is because, despite having zero-tailpipe emission, EV consumes electricity and the source of fuel for electricity generation determines the resultant amount of indirect GHG emissions from EV. Amount of electricity that needs to be generated to run EVs is related to distance travelled and efficiency of the vehicle, after accounting for power generation, transmission and charging efficiencies. Fortunately, 99% of electricity in Brunei is generated from natural gas [65]; a relatively clean source of energy (emitting only 0.181 *kg CO2 equiv. per kWh*) as compared to diesel oil, coal [50], and indeed, from motor gasoline (emitting only 0.240 *kg CO2 equiv. per kWh*) as can be seen from **Table 4**. Despite this, EVs are still environmental worst off than gasoline vehicles.

To reduce GHG emission and to make EVs more environmentally competitive, other clean sources of energy such as solar and wind, need to be considered. In this respect, Brunei has huge potential to shift to solar power generation due to its strategic location [66]. Also, efficiency of power

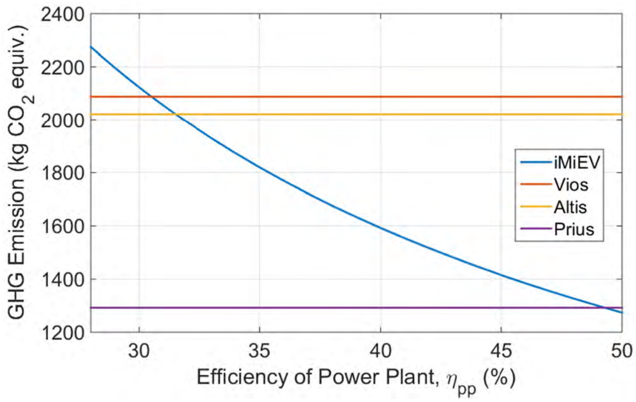


FIGURE 12. Emissions of the different Vehicles, for varying efficiency of power plant.

plant η_{pp} needs to be improved [50]. Increasing η_{pp} from current efficiency of 28.4% to 30.6%, 31.6% and 49.2% make i-MiEV more environmentally competitive to Vios, Altis and Prius, respectively, as shown in **Figure 12**.

IV. CONCLUSIONS

Methodologies to calculate LCC of vehicles and their environmental impact, have been shown and used to analyse feasibility of EVs to compete in a given market, as well as to identify dominant factor which influence feasibility of EVs. Local Brunei data has been used for the purpose.

LCC of i-MiEV (EV) has been calculated to be approximately $USD\$33K$; more expensive than Vios (ICEV) and Prius (HEV) but cheaper than Altis (ICEV). Acquisition cost dominates the LCC of i-MiEV (EV), followed by maintenance cost; with most of the maintenance cost composed of battery replacement cost, and then, operating cost. It has been shown that acquisition cost of i-MiEV (EV) would need to be reduced by 28% to make its LCC to be less than all three vehicles considered in this study.

It is proposed that in order to promote EVs, the government needs to look into subsidy as well as increasing current gasoline price. Increasing gasoline price effectively penalises ICEVs and HEVs. To allow EVs to compete with other vehicles in term of LCC, initial subsidy of $USD\$4103.25$ is proposed with gasoline price increased to $US\$0.6966/litre$. Together with the expected annual decline of between 6-9% on battery price until 2030, EVs shall be able to compete with other vehicles without subsidy in 2030 or earlier.

EV manufacturers also needs to concentrate on acquisition cost of EV; as it has been shown to be the most influential factor in determining affordability of EVs in the local market. Improving fuel efficiency of EVs has minimal effect on LCC of EVs; due to the low electricity price in Brunei.

The study has also looked at environmental effect of EV using the current power generating capability which rely mostly on natural gases. It has been shown that despite EV producing zero-tailpipe emission, it stills produces the most GHG after taking energy generation, transmission and charging efficiency into accounts. To make EV more environmentally friendly, renewable energy generation such as solar or wind energies, needs to be considered. Efficiency of the power plant also needs to be improved; by increasing power plant efficiency to 32% makes EV more environmentally friendly than common ICEVs.

Based on the study, it can be concluded that EVs have the potential to penetrate and compete with established ICEVs and HEVs in the Bruneian market. However, the government needs to look at different methods of promoting EVs; by providing financial incentives such as taxation/subsidy on gasoline and electricity prices, duty vehicles, as well as infrastructure support to facilitate its uptake. Furthermore, to enjoy the benefit from EVs, improvement in efficiency to the power generation and transmission need to be made.

REFERENCES

[1] M. Höök, J. Li, K. Johansson, and S. Snowden, ''Growth rates of global energy systems and future outlooks,'' *Natural Resour. Res.*, vol. 21, pp. 23–41, Mar. 2012.
[2] S. H. Mohr, J. Wang, G. Ellem, J. Ward, and D. Giurco, ''Projection of world fossil fuels by country,'' *Fuel*, vol. 141, pp. 120–135, Feb. 2015.
[3] *Key World Energy Statistics*, Int. Energy Agency, Paris, France, 2017.
[4] A. S. Silitonga, A. E. Atabani, T. M. I. Mahlia, and A. H. Sebayang, ''Techno-economic analysis and environmental impact of fuel economy labels for passenger cars in Indonesia,'' *Renew. Sustain. Energy Rev.*, vol. 15, pp. 5212–5217, Dec. 2011.
[5] A. S. Silitonga, A. E. Atabani, and T. M. I. Mahlia, ''Review on fuel economy standard and label for vehicle in selected ASEAN countries,'' *Renew. Sustain. Energy Rev.*, vol. 16, pp. 1683–1695, Apr. 2012.
[6] A. E. P. Abas and T. M. I. Mahlia, ''Development of energy labels based on consumer perspective: Room air conditioners as a case study in Brunei Darussalam,'' *Energy Rep.*, vol. 4, pp. 671–681, Nov. 2018.
[7] F. Kusumo, A. S. Silitonga, H. H. Masjuki, H. C. Ong, J. Siswantoro, and T. M. I. Mahlia, ''Optimization of transesterification process for *Ceiba pentandra* oil: A comparative study between kernel-based extreme learning machine and artificial neural networks,'' *Energy*, vol. 134, pp. 24–34, Sep. 2017.
[8] M. Faried, M. Samer, E. Abdelsalam, R. S. Yousef, Y. A. Attia, and A. S. Ali, ''Biodiesel production from microalgae: Processes, technologies and recent advancements,'' *Renew. Sustain. Energy Rev.*, vol. 79, pp. 893–913, Nov. 2017.
[9] A. S. Silitonga, A. E. Atabani, T. M. I. Mahlia, H. H. Masjuki, I. A. Badruddin, and S. Mekhilef, ''A review on prospect of *Jatropha curcas* for biodiesel in Indonesia,'' *Renew. Sustain. Energy Rev.*, vol. 15, pp. 3733–3756, Oct. 2011.
[10] H. C. Ong, H. H. Masjuki, T. M. I. Mahlia, A. S. Silitonga, W. T. Chong, and T. Yusaf, ''Engine performance and emissions using *Jatropha curcas, Ceiba pentandra* and *Calophyllum inophyllum* biodiesel in a CI diesel engine,'' *Energy*, vol. 69, pp. 427–445, May 2014.
[11] A. S. Silitonga, H. H. Masjuki, T. M. I. Mahlia, H. C. Ong, W. T. Chong, and M. H. Boosroh, ''Overview properties of biodiesel diesel blends from edible and non-edible feedstock,'' *Renew. Sustain. Energy Rev.*, vol. 22, pp. 346–360, Jun. 2013.
[12] H. C. Ong, H. H. Masjuki, T. M. I. Mahlia, A. S. Silitonga, W. T. Chong, and K. Y. Leong, ''Optimization of biodiesel production and engine performance from high free fatty acid *Calophyllum inophyllum* oil in CI diesel engine,'' *Energy Convers. Manage.*, vol. 81, pp. 30–40, May 2014.
[13] *Technology Roadmap: Biofuels for Transport*, US Int. Energy Agency, Paris, France, 2011, p. 56.
[14] A. S. Silitonga, H. H. Masjuki, H. C. Ong, A. H. Sebayang, S. Dharma, F. Kusumo, J. Siswantoro, J. Milano, K. Daud, T. M. I. Mahlia, W.-H. Chen, and B. Sugiyanto, ''Evaluation of the engine performance and exhaust emissions of biodiesel-bioethanol-diesel blends using kernel-based extreme learning machine,'' *Energy*, vol. 159, pp. 1075–1087, Sep. 2018.

[15] H. B. Aditiya, W. T. Chong, T. M. I. Mahlia, A. H. Sebayang, M. A. Berawi, and H. Nur, "Second generation bioethanol potential from selected Malaysia's biodiversity biomasses: A review," *Waste Manage.*, vol. 47, pp. 46–61, Jan. 2016.

[16] J. Buekers, M. Van Holderbeke, J. Bierkens, and L. I. Panis, "Health and environmental benefits related to electric vehicle introduction in EU countries," *Transp. Res. D, Transp. Environ.*, vol. 33, pp. 26–38, Dec. 2014.

[17] T. Muneer, R. Milligan, I. Smith, A. Doyle, M. Pozuelo, and M. Knez, "Energetic, environmental and economic performance of electric vehicles: Experimental evaluation," *Transp. Res. D, Transp. Environ.*, vol. 35, pp. 40–61, Mar. 2015.

[18] T. Muneer, M. Kolhe, and A. Doyle, *Electric Vehicles: Prospects and Challenges*. Amsterdam, The Netherlands: Elsevier, 2017.

[19] C. C. Chan, "The rise & fall of electric vehicles in 1828–1930: Lessons learned [scanning our past]," *Proc. IEEE*, vol. 101, no. 1, pp. 206–212, Jan. 2013.

[20] F. Kley, C. Lerch, and D. Dallinger, "New business models for electric cars—A holistic approach," *Energy Policy*, vol. 39, pp. 3392–3403, Jun. 2011.

[21] R. R. Heffner, K. S. Kurani, and T. S. Turrentine, "Symbolism in California's early market for hybrid electric vehicles," *Transp. Res. D, Transp. Environ.*, vol. 12, pp. 396–413, Aug. 2007.

[22] *Global EV Outlook 2016*, Int. Energy Agency, Paris, France, 2016.

[23] B. Nykvist and M. Nilsson, "Rapidly falling costs of battery packs for electric vehicles," *Nature Climate Change*, vol. 5, no. 4, pp. 329–332, 2015.

[24] S. Yan, "The economic and environmental impacts of tax incentives for battery electric vehicles in Europe," *Energy Policy*, vol. 123, pp. 53–63, Dec. 2018.

[25] L. K. Mitropoulos, P. D. Prevedouros, and P. Kopelias, "Total cost of ownership and externalities of conventional, hybrid and electric vehicle," *Transp. Res. Procedia*, vol. 24, pp. 267–274, Jan. 2017.

[26] H. L. Breetz and D. Salon, "Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 U.S. cities," *Energy Policy*, vol. 120, pp. 238–249, Sep. 2018.

[27] Y. S. Wong, W.-F. Lu, and Z. Wang, "Life cycle cost analysis of different vehicle technologies in Singapore," *World Electr. Vehicle J.* vol. 4, no. 4, pp. 912–920, 2011.

[28] S. Kara, W. Li, and N. Sadjiva, "Life cycle cost analysis of electrical vehicles in Australia," *Procedia CIRP*, vol. 61, pp. 767–772, Jan. 2017.

[29] A. Elgowainy, M. Wang, F. Joseck, and J. Ward, "Life-cycle analysis of fuels and vehicle technologies A2—Abraham, Martin A," in *Encyclopedia of Sustainability Science and Technology*. Oxford, U.K.: Elsevier, 2017, pp. 317–327.

[30] M. Knowles, "Through-life management of electric vehicles," *Procedia CIRP*, vol. 11, pp. 260–265, Jan. 2013.

[31] M. Mehrali, S. T. Latibari, M. Mehrali, T. M. I. Mahlia, H. S. C. Metselaar, M. S. Naghavi, E. Sadeghinezhad, and A. R. Akhiani, "Preparation and characterization of palmitic acid/graphene nanoplatelets composite with remarkable thermal conductivity as a novel shape-stabilized phase change material," *Appl. Thermal Eng.*, vol. 61, pp. 633–640, Nov. 2013.

[32] M. Amin, N. Putra, E. A. Kosasih, E. Prawiro, R. A. Luanto, and T. M. I. Mahlia, "Thermal properties of beeswax/graphene phase change material as energy storage for building applications," *Appl. Thermal Eng.*, vol. 112, pp. 273–280, Feb. 2017.

[33] K. Palmer, J. E. Tate, Z. Wadud, and J. Nellthorp, "Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan," *Appl. Energy*, vol. 209, pp. 108–119, Jan. 2018.

[34] N. C. Onat, M. Kucukvar, N. N. M. Aboushaqrah, and R. Jabbar, "How sustainable is electric mobility? A comprehensive sustainability assessment approach for the case of Qatar," *Appl. Energy*, vol. 250, pp. 461–477, Sep. 2019.

[35] A. Sheth and D. Sarkar, "Life cycle cost analysis for electric vs. diesel bus transit in an Indian scenario," *Int. J. Technol.*, vol. 10, no. 1, p. 105, 2019.

[36] *Brunei Darussalam's Initial National Communication*, Energy Ind. Dept., Energy Ind. Dept. Prime Minister's Office, EIDPMO, Bandar Seri Begawan, Brunei, 2010.

[37] *Review to Formulate a Roadmap and Draft national Masterplan for a Sustainable Land Transport System for Brunei Darussalam*, SQWChinaLimited, Beijing, China, May 2014.

[38] B. Schmitt. (2017). *World's Top Ten EV Makers, And The Case Of The Missing Teslas*. [Online]. Available: https://www.forbes.com/sites/bertelschmitt/

[39] Mitsubishi. (Nov. 29, 2017). *Mitsubishi Motors. I-MiEV Specifications*. [Online]. Available: http://www.mitsubishi-motors.com

[40] B. S. Dhillon, "Life cycle costing economics," in *Life Cycle Costing for Engineers*. Boca Raton, FL, USA: CRC Press, 2009, pp. 11–25.

[41] P. E. Abas and T. M. I. Mahlia, "Techno-economic and sensitivity analysis of rainwater harvesting system as alternative water source," *Sustainability*, vol. 11, p. 2365, 2019.

[42] L. Merino, F. Caballero, J. R. Martínez-de-Dios, I. Maza, and A. Ollero, "An unmanned aircraft system for automatic forest fire monitoring and measurement," *J. Intell. Robot. Syst.*, vol. 65, no. 1, pp. 533–548, 2012.

[43] M. Spickova and R. Myskova, "Costs efficiency evaluation using life cycle costing as strategic method," *Procedia Econ. Finance*, vol. 34, pp. 337–343, Jan. 2015.

[44] A. A. Robichek and S. C. Myers, "Conceptual problems in the use of risk-adjusted discount rates," *J. Finance*, vol. 21, pp. 727–730, Dec. 1966.

[45] *Economic Planning and Development. FAQ Consumer Protection and Motor Vehicles*, PMO, New Delhi, India, 2017.

[46] G. Berckmans, M. Messagie, J. Smekens, N. Omar, L. Vanhaverbeke, and J. Van Mierlo, "Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030," *Energies*, vol. 10, no. 9, p. 1314, 2017.

[47] O. van Vliet, A. S. Brouwer, T. Kuramochi, M. van den Broek, and A. Faaij, "Energy use, cost and CO_2 emissions of electric cars," *J. Power Sources*, vol. 196, pp. 2298–2310, Feb. 2011.

[48] J. Ranganathan, "The greenhouse gas protocol: A corporate accounting and reporting standard," Standard Rep., 2004.

[49] E. A. Nanaki and C. J. Koroneos, "Comparative economic and environmental analysis of conventional, hybrid and electric vehicles—The case study of Greece," *J. Cleaner Prod.*, vol. 53, pp. 261–266, Aug. 2013.

[50] T. M. I. Mahlia, J. Y. Lim, L. Aditya, T. M. I. Riayatsyah, A. E. P. Abas, and Nasruddin, "Methodology for implementing power plant efficiency standards for power generation: Potential emission reduction," *Clean Technol. Environ. Policy*, vol. 20, no. 2, pp. 309–327, Dec. 2018.

[51] R. J. Alonzo, "Electrical transmission and distribution systems," in *Electrical Codes, Standards, Recommended Practices and Regulations*, R. J. Alonzo, Ed. Boston, MA, USA: William, 2010, ch. 12, pp. 405–467.

[52] T. Quiroga. (Sep. 29, 2012). *2012 Mitsubishi i Electric Vehicle*. [Online]. Available: http://www.caranddriver.com/

[53] Numbeo. (2017). *Traffic in Bandar Seri Begawan, Brunei*. Accessed: Dec. 25, 2017. [Online]. Available: https://www.numbeo.com/traffic

[54] Arlington. (2017). *Toyota Battery Life Expectancy and Replacement*. Accessed: Sep. 29, 2017. [Online]. Available: http://www.toyotaarlington.com

[55] Toyota. (2017). *Corolla Altis—A Legend Redefined*. Accessed: Dec. 25, 2017. [Online]. Available: www.nbt.com.bn/cars

[56] Toyota. (2017). *2017 Prius*. Accessed: Dec. 5, 2017. [Online]. Available: https://www.toyota.com/prius/

[57] B. C. Chew, S. R. Hamid, R. M. Nawi, and H. Muzaimi, "Green marketing strategy to enhance corporate image: Case study in UMW toyota motor SDN BHD," Tech. Rep., 2016.

[58] Toyota. (2016). *Toyota Vios, A Class Beyond*. Accessed: Dec. 25, 2017. [Online]. Available: http://www.nbt-brunei.com/cars

[59] (2017). *Electricity Prices*. Accessed: Dec. 25, 2017. [Online]. Available: https://www.globalenergyprices.com

[60] (2017). *Gasoline Prices*. Accessed: Dec. 25, 2017. [Online]. Available: http://www.globalpetrolprices.com

[61] N. Wang, L. Tang, and H. Pan, "A global comparison and assessment of incentive policy on electric vehicle promotion," *Sustain. Cities Soc.*, vol. 44, pp. 597–603, Jan. 2019.

[62] T. K. Knobbe, "Comparative analysis of fuel source consumption and economic costs of razorback transit among alternative fuel sources," Tech. Rep.

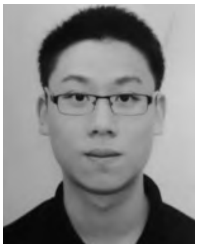
[63] S.-Q. Dotse, L. Dagar, M. I. Petra, and L. C. De Silva, "Evaluation of national emissions inventories of anthropogenic air pollutants for Brunei Darussalam," *Atmos. Environ.*, vol. 133, pp. 81–92, May 2016.

[64] TheWorldBank. (2014). *Electric Power Transmission and Distribution Losses*. Accessed: Dec. 19, 2017. [Online]. Available: https://data.worldbank.org

[65] R. A. Masri, "New technology options for improving generating efficiency of Brunei power system," Tech. Rep., 2015.

[66] A. Q. Malik, "Assessment of the potential of renewables for Brunei Darussalam," *Renew. Sustain. Energy Rev.*, vol. 15, pp. 427–437, Jan. 2011.

A. E. PG ABAS received the B.Eng. degree in information systems engineering, and the Ph.D. degree in communication systems from Imperial College, London, in 2001 and 2005, respectively. He is currently an Assistant Professor in system engineering with the Faculty of Integrated Technologies, Universiti Brunei Darussalam. His current research interests are data analysis, security of info-communication systems and design of photonic crystal fiber in fiber optics communication.



JED YONG received the B.Eng. degree in chemical and process engineering from Universiti Brunei Darussalam, in 2018. He is currently a Chemical and Process Engineer with Hengyi Petrochemical, Brunei, working on numerous Hengyi project in Brunei and China.

T. M. I. MAHLIA received the Ir. degree in mechanical engineering from Syiah Kuala University, Banda Aceh, Indonesia, and the M.Eng.Sc. degree in engineering and the Ph.D. degree from the University of Malaya, in 1997 and 2003, respectively. He was a Professor with the University of Malaya and Universiti Tenaga Nasional. In 2018, he was invited to join the School of lnformation, Systems and Modeling Faculty of Engineering and Information Technology, University of Technology Sydney, as a Distinguished Professor. His research interests energy systems, energy policy, energy modeling, energy efficiency, and energy management. He is one of the Highly Cited Researchers, in 2017 and 2018, respectively.

M. A. HANNAN (M'10–SM'17) received the B.Sc. degree in electrical and electronic engineering from the Chittagong University of Engineering and Technology, Chittagong, Bangladesh, in 1990, and the M.Sc. and Ph.D. degrees in electrical, electronic, and systems engineering from the Universiti Kebangsaan Malaysia (UKM), Bangi, Malaysia, in 2003 and 2007, respectively. He was a Professor with the National University of Malaysia. He is currently a Professor of intelligent systems with the Department of Electrical Power Engineering, College of Engineering, National Energy University, Malaysia. His research interests include intelligent controllers, power electronics, hybrid vehicles, energy storage systems, image and signal processing, and artificial intelligence. He is currently an Associate Editor of IEEE Access.