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Impact of electric vehicles use on overall electricity demand

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ABSTRACT

This paper presents a method for determining the electricity demands under condition of the use of battery electric vehicles (BEVs) in the transport sector according to the assumption that traditional internal combustion vehicles (ICVs) will be replaced by BEVs. The rate of oil used by the land transport sector at present, including the energy efficiency of ICVs and BEVs, were considered under the principle of energy conservation. The growth rate of energy consumption was estimated from rate of past fuel consumption. The trend in the ordinary electricity demand was calculated from previously recorded data using a linear regression method. The electricity demand by the land transport sector and the rate of growth were merged with the ordinary electricity demand via logistic regression. This method was applied to the transport sector in Thailand, assuming BEVs would constitute 30% of land transport. The results revealed the amount of electricity that should be prepared for rising up of BEVs in transport world, and BEVs will cause a perceptible change in the previous trend of overall electricity demand.

Keywords: electric vehicles; electricity demand; fuel consumption; Li-ion battery

1. INTRODUCTION

Fossil fuels play a role as the main energy source in the transport sector at present but it is known that we cannot rely on them forever. Crude oil is projected to deplete within the next 40 to 80 years and other types of fossil fuels will deplete one day, also. Moreover, environmental factors, such as air pollution from vehicles, are a problem for many cities. These factors have caused several countries to generate a plan to promote the use of vehicles powered by an alternative source of energy (Higgins et al., 2012). Today, many types of vehicles are under development in response to the oil depletion situation, and these vehicles can be classified into the following four categories according to the type of power source used:

1) Powered by fossil fuels or renewable fuels: Vehicles in this category have a heat engine in their propulsion system and use gasoline, diesel fuel, ethanol, bio-diesel or natural gas as their main energy source. Internal combustion vehicles (ICVs) and hybrid electric vehicles (HEVs) are classified in this category. In fact, HEVs have both a heat engine and an electric motor in their propulsion system, where the electricity for driving the electric motor is generated from the heat engine.

2) Powered by fossil fuels or renewable fuels and electricity: Plug in HEVs (PHEVs) are classified into this category. Similar to HEVs, PHEVs contain a heat engine and an electric motor in their propulsion system. However, PHEVs can connect to the power grid to charge their battery and can use this electrical energy to drive the electric motor.

3) Powered by electricity: These vehicles contain only an electric motor propulsion system and are exclusively powered by electricity from the power grid. Battery electric vehicles (BEVs) are classified into this category.

4) Powered by hydrogen: Hydrogen fuel cell vehicles (HFCVs) are classified into this category. As in BEVs, HFCVs contain only an electric motor in their propulsion system. However, in HFCVs, the electricity that is used to drive the motor is derived from the fuel cell (FC). There are many types of FCs that use different types of energy sources, but the FCs in HFCVs use hydrogen as the energy source.

The impact of HEVs and PHEVs on the fossil fuel or renewable fuel sector can be combined with the impact of ICVs, and the impact of PHEVs on the power grid can be combined with impact of BEVs. We believe that HEVs and PHEVs serve as a bridge technology from heat engine propulsion to pure electric motor propulsion. Rising up of BEVs possibly cause decreasing not only ICVs in transport sector but also HEVs and PHEVs (Higgins et al., 2012). In addition, the lack of an entire internal combustion engine system, a drivetrain and a fuel tank in BEVs represents a savings of up to 4,000 US$ per vehicle (IEA, 2011). A proper plan for infrastructure investment for the support of BEVs using, requires data concerning future energy demand. Prediction of electricity demand by BEVs is based on energy consumed per distance (kWh/km). The results data could vary substantially between locations, depending on the nature of the route, traffic condition, behavior of driving and the load of each vehicle. Flat ground routes with traffic mobility spend significantly less energy than routes containing valleys or traffic jams. In addition, for the same route condition, an empty vehicle spent significantly less energy than a full load vehicle. Electricity required in charging a passenger EV can vary between 2 kWh to 20 kWh each time (Higgins et al., 2012). Khoo and colleagues (Khoo et al., 2014) studied trial data of using BEVs in Australia, Victoria state, by using descriptive statistics. Charging behavior and prediction on daily load and peak demand are presented as results. The other example is the study by Qian and colleagues (Qian et al., 2011) which was based on simulating four EV charging scenarios and applied to a typical U.K. distribution system. The results indicate that not only supply the load demand as sufficiently when EVs penetrate into the transport sector but management of the time of starting charging EVs is also necessary. Starting charging several EVs during the peak load time can cause a new peak to the power system.

This paper examined the topic of overall electricity demand by BEVs when they participate the transport sector significantly from a difference technique. This approach takes into account the fuel consumption by ICVs of land transport in the past which based on energy conservation law and principle of thermodynamics. The amount of electricity used by BEVs has been forecasted using real-world data. These data include the annual fuel consumption by the land transport sector as well as the efficiencies of heat engines, electric motors, batteries and energy saving systems (regenerative braking). It can be used for predicting BEVs electricity demand at any location, due to the influences of the traveling route, the traffic conditions and the load of each vehicle. It can be used for both in a single vehicle or many vehicles. The details in derivation of the equation and how the numerical values for each variable coming are described in topic 2. Validity proving of the result equation is presented in topic 3.1. The secondary result presented in topic 3.2 is the electricity demand from power distribution system. Obtaining from applying the equation (17) to the data concerning the energy situation in Thailand.

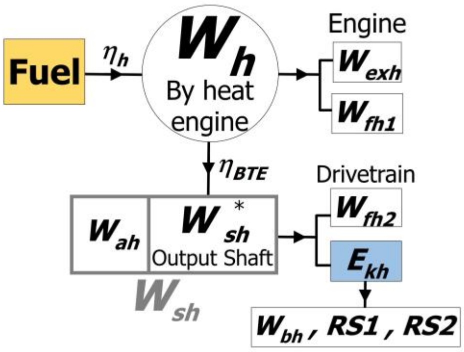

Figure 1 Energy flow chart for an internal combustion vehicle

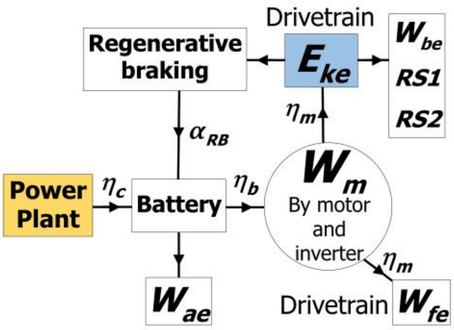

Figure 2 Energy flow chart for a battery electric vehicle

2. MATERIALS AND METHODS

In any transportation system, there must be motion of some vehicles, and the energy of this motion is termed kinetic energy. The amount of kinetic energy needed for traveling depends on many factors, such as characteristics of the vehicle, the load and the driving style, especially the frequency of braking. Summation of kinetic energy from all vehicles in the transport sector is defined as the total energy of transportation. It is produced from combustion reaction in heat engines.

2.1 Energy of land transportation from heat engines

In an internal combustion engine, the work performed by the engine is transferred via 4 processes (Eckerle, 2011), i.e., 1) output at the engine's drive shaft (W^*_{sh}), 2) used by vehicle accessories (W_{ah}), 3) loss from friction in the engine (W_{fh1}), and 4) spent in the gas exchange process (W_{exh}). As shown in Figure 1, we can state that

$$W_h = W^*_{sh} + W_{ah} + W_{fh1} + W_{exh} \quad (1)$$

The work from the engine's drive shaft is transferred to be kinetic energy of the vehicle (E_{kh}) and some is lost by friction at any part of the drivetrain (W_{fh2})

$$W^*_{sh} = E_{kh} + W_{fh2} \quad (2)$$

All of the kinetic energy of the vehicle is lost due to the work of vehicle braking (W_{bh}), wind resistance ($RS1$) and rolling resistance ($RS2$).

Net kinetic energy of a vehicle from the engine is

$$E_{kh} = W_h - (W_{ah} + W_{fh1} + W_{fh2} + W_{exh}) \quad (3)$$

2.2 Energy of land transportation from electric motors

If electric vehicles (EV) are used the energy of land transportation will come from the electric motor. In a BEV energy in the form of electricity is charged to the battery, and energy from discharging (ε_d) is spent in the following two ways (see Figure 2):

1) energy supply for vehicle accessories (W_{ae})

2) energy supply for the electric motor; the work performed by the motor (W_m) is transferred to

2.1) kinetic energy of the vehicle (E_{ke})

2.2) energy loss from friction at the drivetrain (W_{fe}).

Based on the energy conservation principle:

$$\varepsilon_d = W_{ae} + W_m / \eta_m \quad (4)$$

where η_m is the energy efficiency of the electric motor, including the efficiency of the inverter. The function of the inverter is to convert the DC signal from the battery to an AC signal that is fed to the motor. Work performed by the motor is spent in two ways as well.

Therefore, (4) can be rewritten as

$$\varepsilon_d = W_{ae} + (E_{ke} + W_{fe})/\eta_m \tag{5}$$

By rewriting (5), the kinetic energy for traveling using a BEV is

$$E_{ke} = \eta_m \varepsilon_d - (\eta_m W_{ae} + W_{fe}) \tag{6}$$

In a conventional heat engine vehicle, all of the kinetic energy is completely lost when the vehicle stops. However, in an EV, there is a system termed "regenerative braking" (RB). RB is a piece of equipment that converts some of the energy loss from braking into electricity to recharge the battery. This process helps save energy. Research by Yang and his colleagues (Yang et al., 2009) showed that RB can increase the traveling range of an EV by approximately 16.2%. The effect of this system on (6) is as follows.

Assume the energy spent by a vehicle is proportional to the distance traveled and define the "regenerative braking factor" (α_R) as

$$\alpha_R = \mathrm{R}^*/\mathrm{R} \tag{7}$$

where R^* is range that an EV with RB system can travel in a full charge and R is the range that an EV lacking an RB can travel in a full charge. We found that

$$E^*_{ke} = \eta_m \alpha_R \varepsilon_d - (\eta_m W^*_{ae} + W^*_{fe}) \tag{8}$$

where E^*_{ke}, W^*_{ae} and W^*_{fe} for an EV with an RB, represent the kinetic energy, the energy supplied for vehicle accessories and the energy loss from friction respectively. Term $\alpha_R \times \varepsilon_d$ is the net energy discharged from the battery when the effect of an RB is counted and ε_d is the energy discharged from battery not including the effect of the RB. From the paper by Yang and colleagues, α_R is 1.162.

2.3 ICVs replaced by BEVs

Based on the following postulation:

1) if vehicle shape, weight and load are approximately equivalent between BEVs and ICVs,

2) if both vehicle types travel in the same landscape using the same routes, and

3) if both vehicle types share the same traffic conditions and driving styles,

then both vehicle types will require an equivalent amount of kinetic energy in traveling:

$$E^*_{ke} = E_{kh} \tag{9}$$

When E_{kh} and E^*_{ke} from (3) and (8), respectively, are substituted into (9), the equation becomes

$$\eta_m \alpha_R \varepsilon_d = W_h - W_{exh} - W_{fh1} + [(\eta_m W^*_{ae} + W^*_{fe}) - (W_{ah} + W_{fh2})] \tag{10}$$

Work done by the engine (W_h) is spent by vehicle's accessories (W_{ah}) about 1.6% and for friction of any part of the vehicle (W_{fh2}) about 1.8% (Eckerle, 2011). The terms (η_m W^*_{ae} + W^*_{fe}) are energy for driving vehicle accessories and lost energy by friction at any parts of the vehicle, like as the terms (W_{ah} + W_{fh2}). These terms cancel each other and then we can neglect both of them from our calculation. Therefore, the simplified form of (10) is:

$$\eta_m \alpha_R \varepsilon_d = W_h - W_{exh} - W_{fh1} \tag{11}$$

The right hand side of (11) is the work output at the engine's drive shaft (W^*_{sh}) and from the definition of Brake thermal efficiency (η_{BTh}) we can rewrite (11) as

$$\eta_m \alpha_R \varepsilon_d = \eta_{Bth} Q \tag{12}$$

where Q is the heat energy from combustion reaction in heat engine of an ICV. Equation (12) implies that we can indicate the energy that is needed to support BEVs in the case that they are used instead of ICVs. Data from the website of the American Physical Society (APS, 2010) shows that *1 ton of oil equivalent (toe) = 11,630 × 10^-6^ GWh*, where 1 toe is the heat energy from burning 1 ton of crude oil, as a lower heating value (LHV), and gigawatt-hour (GWh) is an energy unit that is typically used for electricity. If the annual fuel consumption by land transportation (all vehicles in the country) is defined as *Atoe*, then

$$\sum Q_1 = (11{,}630 \times 10^{-6})\, Atoe \qquad (13)$$

From (12) and (13), we obtain

$$\sum \varepsilon_d = \frac{\eta_{BTh}\,(11{,}630 \times 10^{-6})\, Atoe}{\eta_m\, \alpha_R} \qquad (14)$$

where $\Sigma\varepsilon_d$ is total energy discharged from all of BEVs batteries in GWh.

2.4 How to find overall BEVs electricity demand

The energy efficiency of a battery (η_b) is defined as the electrical energy from discharging (ε_d) divided by the electrical energy added to the battery during charging (ε_c):

$$\eta_b = \varepsilon_d / \varepsilon_c \qquad (15)$$

There is also energy loss at the battery charger. The energy efficiency of the battery charger (η_c) is the electrical energy that is added to the battery during charging (ε_c) divided by the electrical energy that is consumed by the battery charger (ε_s):

$$\eta_c = \varepsilon_c / \varepsilon_s \qquad (16)$$

Indeed, ε_s is the electricity from the power station. By substituting (15) and (16) into (14), we obtain:

$$\sum \varepsilon_s = \frac{\eta_{BTh}\,(11{,}630 \times 10^{-6})\, Atoe}{\eta_m\, \eta_b\, \eta_c\, \alpha_R} \qquad (17)$$

where $\Sigma\varepsilon_s$ is total electricity demand in GWh and *Atoe* is annual fuel consumption by the land transport sector in toe. This equation can be applied for finding the electricity demand for BEVs ($\Sigma\varepsilon_s$) in the case that all ICVs are replaced.

2.5 Numerical value of each variable

The descriptions of the numerical values for each variable in the calculation of the electrical consumption requirement are as following.

2.5.1 Brake thermal efficiency (η_{BTh})

Data from experimental research (Krishna Reddy et al., 2010) reported that diesel engine powered by diesel fuel operated with constant speed 1,500 rpm, and brake thermal efficiency varies between 15-30% under load 20-80%. We had used 22.5% (median between 15-30%) for brake thermal efficiency of diesel engine. Reporting by the official U.S. government source (EPA, 2016a) the power to wheels is 18-25% in gasoline vehicles. We had used 21.15% (median) for brake thermal efficiency of Otto engine.

Table 1 Annual fuel used by land transport in Thailand (EPPO, 2014 and 2015)

Year	2004	2005	2006	2007	2008	2009	2010	2011	2012
Consumption (ktoe)	17,842	18,309	17,934	18,358	17,705	19,066	19,234	20,331	21,913

Regarding the proportion of fuel consumption from land transport in Thailand for each fuel type, we had referred to the report "Thailand's energy situation in 2010 and trend in 2011" (EPPO, 2010). LPG and NGV had combined with gasoline, which represents 44.06% of all fuel consumption by all Otto engines and the left 55.94% belonging to diesel engines. Each type of fuel has a different heating value but all expressed in toe unit which the effect of the heating value considered already. The brake thermal efficiency used in the calculation is the average of the diesel and Otto engine weights multiplied by their percentage of fuel consumed, as follow:

$$\eta_{BTh} = 0.5594\eta_{BTh,Diesel} + 0.4406\eta_{BTh,Otto} \qquad (18)$$

where $\eta_{BTh,Diesel}$ and $\eta_{BTh,Otto}$ are the brake thermal efficiency of diesel and Otto engines, respectively.

From (18), we obtained η_{BTh} = 22%. The Energy Efficiency & Renewable Energy Office of the U.S. Department of Energy (EERE, 2010) reported that vehicles that are 10 or even 15 years old will exhibit little decrease in fuel economy if properly maintained. Therefore, the decreasing efficiency of heat engines used for a long period is neglected.

2.5.2 Trend of fuel consumption by the land transport sector

The data shown in Table 1 were provided by the Energy Policy and Planning Office of Thailand (EPPO, 2014 and 2015). Assuming that the growth rate is linear and by using a linear regression method, the equation for predicting fuel consumption each year is

$$Atoe = 426.63\text{k}(t - 2003) + 16{,}830\text{k} \qquad (19)$$

(r^2 = 0.7148), where, k is 1000 and t is the calendar year. By assuming that the growth rate of energy demand is identical whether using ICVs or BEVs, we can estimate the electricity demand from using BEVs by substituting the *Atoe* from (19) into (17). However, this value probably significantly deviates from the actual value because the regression equation was generated from data from only 9 years and because this prediction is for a year that is rather far in the future.

Next, let consider the Nissan Leaf, which is a passenger electric vehicle that is available at present. Many of the basic data obtained from the official websites of Nissan (Nissan, 2016).

2.5.3 Efficiency of the motor and the inverter (η_m)

The Nissan Leaf uses an 80 kW AC synchronous electric motor that produces 107 horsepower (HP). Generally, a motor of this size displays 90-95% efficiency (Waide and Brunner, 2011), and its peak efficiency is above 97% between 5,000 and 9,000 rpm (Burress, 2013). The current from the battery must go through an inverter before it travels to the motor. In general, the efficiency of the inverter is approximately 95% when the speed of the motor is between 1,000 and 10,000 rpm (Burress, 2013). These values led us define η_m as 0.90.

2.5.4 Efficiency of the battery (η_b)

The Nissan Leaf 2016 uses an Li-ion battery pack with a capacity of 24 kWh. The battery producer for the Nissan Leaf reported that the nominal voltage of their Li-ion cell is 3.75 V (AESC, 2013). The battery pack is composed of 48 modules (in series), such that each module is connected to 2 Li-ion cells in parallel and 2 Li-ion cells in series (NHTSA, 2013). The net nominal voltage of this battery pack is approximately 360 V. Pop and colleagues (Pop et al., 2007) reported that the electromotive force (Emf) will decrease from 4.175 V to 3.7 V when the state of charge (SOC) of the battery is decrease from 100% to 20%. Thus, we assumed the average Emf to be 3.94 V.

The loss energy from the discharging process can be calculated as

$$E_{loss} = R_i I^2 t \quad (20)$$

where E_{loss} is energy loss at the battery, R_i is the internal resistance of the battery, I is the current flow through the battery and t is the duration of current flow.

An experimental study (Van Mierlo et al., 2009) reported that a Li-ion battery pack (4 parallel groups of Li-ion cells, each containing 8 Li-ion cells in series) displays approximately 86 % energy efficiency for DC of 4.6 A at an SOC of 100-15%. However, this value corresponds to the efficiency of only the early cycles. The change in the energy efficiency of an Li-ion battery over many cycles has rarely been discussed to date. When attempting to calculate the energy loss at the battery using (20) for the case in which the battery has been used for many cycles, we have to know the internal resistance and the discharging current at the given moment. Van Mierlo and colleagues (Van Mierlo et al., 2009) studied 3 types of Li-ion cells with an average internal resistance at a temperature of 25 °C and 100% SOC of 18.8 mΩ (early cycles), which increased to approximately 29.7 mΩ at 15% SOC and the same temperature. Thus, the median of internal resistance is 24.25 mΩ; we used this value as the internal resistance of a fresh Li-ion cell. Xu and colleagues (Xu et al., 2014) studied Li-ion 4 battery packs and used a multiple linear regression method to describe the evolution of internal resistance as a function of battery cycles. At a discharge current rate of 0.4 C and 50% SOC, the internal resistance increased approximately 20% after 1,000 cycles (1 C refers to the amount of current discharged by the entire battery in 1 hour, and 0.4 C refers to 40% of 1 C). We assumed that the internal resistance increases linearly with the discharging cycle. The relationship between the internal resistance (R_i), the discharge current (I'_d) and the battery voltage (V'_b) is

$$V'_b = Emf - I'_d R_i \quad (21)$$

where Emf is the electromotive force of the battery.

The main obstacle in calculation the discharge current is that both the current and the voltage change when the internal resistance increases. However, even if the resistance of the battery changes, the energy consumption behavior of the device is independent of battery health. The rate of energy consumption of a device is identical between a new and an old battery. Only at late cycles, battery will run out of energy more quickly. That is, the rate of energy discharged from the battery (P_b) at early cycles is equal to that at late cycles:

$$P_b = V_b I_d = V'_b I'_d \quad (22)$$

where V_b and I_d are the operating voltage of battery and the discharged current at early cycles respectively, and V'_b and I'_d are the operating voltage and the discharged current at late cycles, respectively. Multiplying (21) by I'_d to obtain a quadratic equation which the solution is

$$I'_d = \frac{Emf - \sqrt{Emf^2 - 4R_i P_b}}{2R_i} \quad (23)$$

We can find the discharged current at any cycle from (23). However, in finding energy loss at any cycle from (20), we must know the duration of current discharge. The capacity of the battery directly correlates with the duration of current discharge or the time of device operation.

Table 2 Theoretical calculation for energy efficiency of an Li-ion battery as a function of battery cycles

General specifications of the battery	Cell connection	Battery health (N-Cycle)	Internal resistance (mΩ)	Operating time (h)	Energy stored in the battery (J)	Rate of energy discharge from the battery (W)	Discharged current (A)	Operating voltage (V)	Energy loss (J)	Energy efficiency
24 kWh *Emf* 378 V Nominal voltage 360 V 192 cells	2P,2S × 48MS	0	1,164	2.00	86.40×10^6	12,000	35.7	336	10.66×10^6	**.877**
		1,000	1,397	1.62	69.98×10^6		36.7	327	10.99×10^6	**.843**
		2,000	1,630	1.24	53.57×10^6		38.0	316	10.48×10^6	**.804**
		3,000	1,862	0.86	37.15×10^6		39.4	305	8.95×10^6	**.759**

* P = Parallel S = Series, MS = Modules connected in series, Internal resistance 24.25 mΩ/cell

Table 3 The numerical data of the variables used for electricity demand calculation

η_{BTh}	η_b	η_c	η_m	α_R
0.22	0.84	0.83	0.90	1.162

Zou and colleagues (Zou et al., 2015) reported that the capacity reduction in an Li-ion battery is linearly associated with the number of battery cycles and decreases approximately 19% after 1,000 cycles. The theoretical calculates of the energy efficiency of an Li-ion battery as a function of battery cycles in a BEV is shown in Table 2 under the following three conditions.

1. The rate of energy consumption by the device with an old battery is the same as that with a new battery (P_b = constant).

2. The internal resistance of the battery increases by 20% per 1,000 cycles.

3. The energy capacity of the battery decreases by 19% per 1,000 cycles.

The initial variables are placed in white cells in Table 2. Consider a BEV, Nissan Leaf can travel 160 km by a fully charge. If we assume the average speed to be 80 km/h then the duration of current flow is 2 h. We had use this number as an operating time of a BEV per a fully charging. The numbers from calculation are placed in shaded cells of Table 2 and the average efficiency of the battery was set as 0.84.

2.5.5 Efficiency of the battery charger (η_c)

The Nissanusa.com website (Nissan, 2016) specifies that there are three modes to recharge the battery of a Nissan Leaf: 1) AC 120 V 16 A, 2) AC 208-240 V 12-80 A or 3) DC 300-600 V. Each mode of recharging displays a different in energy efficiency. Recharging the battery while it has approximately 20-30% of its energy left results in high efficiency and long performance (Nissan, 2016). We chose to consider the recharging efficiency at 220V. The Nissanusa.com website reported that 220 V 3.3 kW onboard charging from 20% to 100% takes 7 hours. Follow this condition the energy used for charging is 23.1 kWh, and 80% capacity of a Nissan Leaf battery (24 kWh) is 19.2 kWh. Then the efficiency of charging is 0.83.

3. RESULTS AND DISCUSSION

3.1 Checking reliability of the theory by comparing with real tests

The fuel economy data of ICV and BEV which have been accepted by The U.S. Environmental Protection Agency (EPA) are referenced as the data from laboratory tests. In ICV, traveling range per fuel consumption (mile per gallon or *MPG*) is measured under controlled condition. The driving wheels of a vehicle will be placed on the equipment called dynamometer for measuring the distance of driving. The rate of the fuel consumption is measured via exhaust gas from tail pipe (EPA, 2016b). Step of accelerating and braking on test driving is under a standard procedure specified by the U.S. federal law. In BEV, the traveling range and power consumption is measured as kWh/mile and mile per gallon equivalent (*MPG*e) under the procedure similar to ICV. The amount of electricity consumption for traveling 100 km by a BEV from laboratory testing will be compared with the electricity for compensate gasoline which consumed by a similarly weight of ICV under the same distance of traveling. However, equation (17) must be a little bit reformed for compatibility with the primary data from EPA (EPA, 2016c) which stated in *MPG*. The heating value and mass density of low-sulfur gasoline is 42.358 MJ/kg (LHV) and 2.830 kg/gal respectively (DOE, 2015). From these facts and from the definition of *MPG*, equation (17) can be rewritten as

$$\varepsilon_s \text{ per100km} = \frac{\eta_{BTh} \times 2{,}069}{\eta_m \, \eta_b \, \eta_c \, \alpha_R \, MPG} \qquad (24)$$

where *MPG* is number of mile per gallon provided by EPA, ε_s per 100 km is electricity in kWh for support a BEV for compensate gasoline that ever consumed for traveling 100 km by an ICV. We assume that a fresh Li-ion battery is used to power a BEV in laboratory testing then the efficiency of a fresh Li-ion battery (0.88) was chosen as η_b.

The results from (25) are shown in the rightmost column of Table 4. The data of *MPG*, *MPG*e and *kWh/100km* in the fourth column all were taken from EPA fuel economy (EPA, 2016c). The abbreviation Hwy means testing procedure that simulates highway traffic, City means testing procedure that simulates city traffic and Comb means combine 45% of Hwy with 55% of City. In consideration Tesla Model S was excluded because it is rather heavier than the other similar class EVs. Under highway traffic condition the results of calculation for electricity demand by a BEV are lower than the results from laboratory about 20%, under city traffic condition the results of calculation are higher than the results from laboratory about 15% and under combination condition the theoretical results are lower than the laboratory testing results about 5-10%. The deviation possibly occurs because the average velocity of ICV on the highway is higher than the velocity in the urban area (most heat engines has more efficiency at high round speed). Another is less work of RB in a BEV when traveling on the highway due to less of braking and curb weight (also shown in Table 4) of a BEV is rather heavier than an ICV with similar model. It can be seen that the theoretical results can be reliable fairly and even in the different traveling condition.

3.2 Trend of overall electricity demand in the case that 30% of land transport in Thailand will be BEVs

By setting *Atoe* to be 1000 ktoe and substitute into (17) using energy efficiency data from Table 3, we found that to replace ICVs by BEVs, every 1,000 ktoe of fossil fuel used must be compensated by 3,510 GWh of electricity. However, to determine the overall electricity demand in addition to the overall energy efficiency, we have to know the following:

1) the amount of fossil fuels that have been consumed in the past and its growth trend; and

2) the market share of BEVs in the transport sector.

Table 4 Theoretical prediction for power demand by a BEVs from the fuel that is used by an ICV on the same distance traveling

Vehicle category	Vehicle model	Curb weight (lbs)	EPA fuel economy				Theoretical prediction (kWh/100km)
				(MPG)	(MPGe)	(kWh/100km)	
BEV	Nissan Leaf (2016)	3,243-3,276	Hwy		101	21.1	
			City		126	16.9	
			Comb		114	18.6	
	Ford Focus electric (2015)	3,624	Hwy		99	21.1	
			City		110	19.3	
			Comb		105	19.9	
	Tesla Model S 70kWh-battery pack (2016)	4,647	Hwy		90	23.3	
			City		88	23.9	
			Comb		89	23.6	
ICV	Ford Focus FWD 1.0L 3Cyl Manual 6spd (2015)	2,907	Hwy	40			14.9
			City	29			20.6
			Comb	33			18.1
	Nissan Sentra 1.8L 4Cyl Auto (2016)	2,858	Hwy	39			15.3
			City	29			20.6
			Comb	33			18.1
	Honda Accord Sport 2.4L 4Cyl (2015)	3,342	Hwy	35			17.0
			City	26			22.9
			Comb	29			20.6
	Honda Civic 1.5L 4Cyl Auto (2016)	2,795	Hwy	41			14.5
			City	31			19.2
			Comb	35			17.0
	Toyota Corolla Eco 1.8L 4Cyl Auto (2015)	2,855	Hwy	38			15.7
			City	29			20.6
			Comb	32			18.6

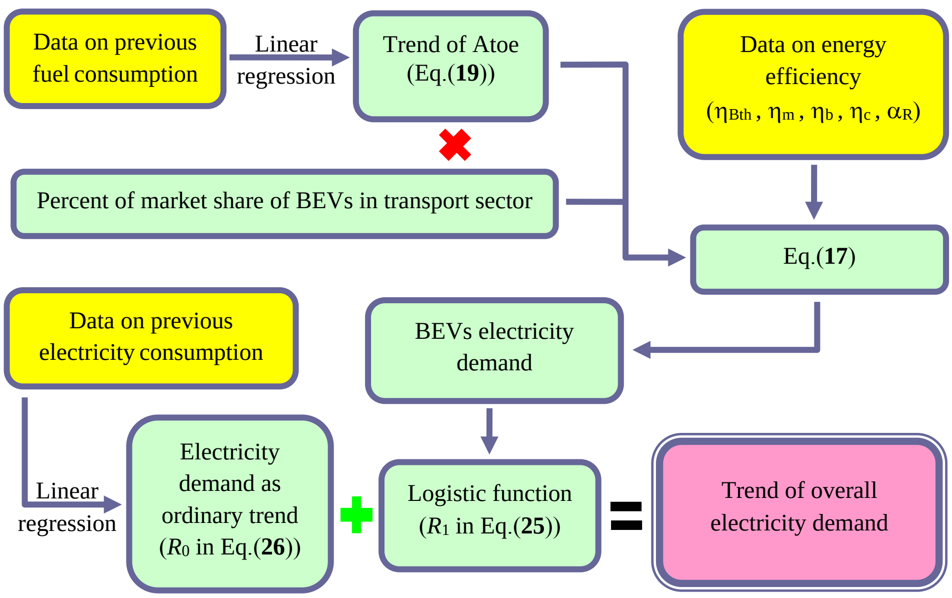

Figure 3 Diagram describing the steps for the calculation of the overall electricity demand

The data of the energy situation in Thailand shown in Table 1 is used as a case study. By substituting the fuel consumption (Atoe) in 2012 into (17), we found that the electricity demand to compensate for all fuel used in land transport is 76,895 GWh/year. This is rather a large amount which is comparable to 48% of all domestic electricity consumption in Thailand in 2012 (shown in Table 5), but it will not occur abruptly. Changing of electricity demand will depend on rate of increase of BEVs in each year. Rapidly increasing of EVs will cause rapidly increasing of the electricity demand also. There is no plans or policies regarding electric vehicles from the Thai government at present. It is possible that many types of vehicles classified by form of energy requirement may be common in the transport sector in the future (Higgins et al., 2012).

Trend of the overall electricity demand was determined under these 3 conditions.

1) BEVs will replace ICVs.

2) BEVs will start to be adopted significantly in calendar year 2020.

3) At end of year 2035 the percentages of BEVs in the transport sector will be 30% and this percentage will be maintained thereafter.

Let R_1 be the electricity demand for all BEVs in the transport sector at each moment. Following the conditions 1) and 3), equation (17) must be multiplied by 0.3 and placed as the upper limit of the logistic regression function:

$$R_1 = 0.3 \times \frac{\sum \varepsilon_s}{1 + e^{(-\mu(t-t_m))}} \quad (25)$$

where $0.3\Sigma\varepsilon_s$ represents the electricity consumption by all BEVs when they occupy 30% of land transport sector, μ is the coefficient reflecting the width of the logistic regression curve, t is the calendar year, and t_m is the calendar year corresponding to the inflection point of the logistic regression curve. Following the conditions 2) and 3), the numerical values for t_m and μ are 2027.5 and 0.65, respectively.

The ordinary annual electricity consumption from all sectors other than the transport sector in Thailand data are shown in Table 5. Trend of the electricity demand rather constantly increases, the time series of annual electricity consumption determined from the linear regression is

$$R_0 = 4779.0t - (9.4609 \times 10^6) \quad (26)$$

where R_0 is the annual electricity consumption (in GWh) under ordinary conditions, t is the calendar year. The statistical correlation coefficient (r) of (26) is r^2 = 0.9844. The overall electricity demand (R) is

$$R = R_0 + R_1 \quad (27)$$

Table 5 Annual electricity consumption in Thailand (EPPO, 2011 and 2015)

Year	1991	1992	1993	1994	1995	1996	1997	1998
Consumption (GWh)	49,225	56,006	62,180	69,651	78,880	85,924	92,725	92,134
Year	1999	2000	2001	2002	2003	2004	2005	2006
Consumption (GWh)	90,414	96,781	103,165	100,091	106,987	115,101	121,240	127,879
Year	2007	2008	2009	2010	2011	2012	2013	2014
Consumption (GWh)	133,113	135,520	135,181	149,301	148,855	161,779	164,341	168,620

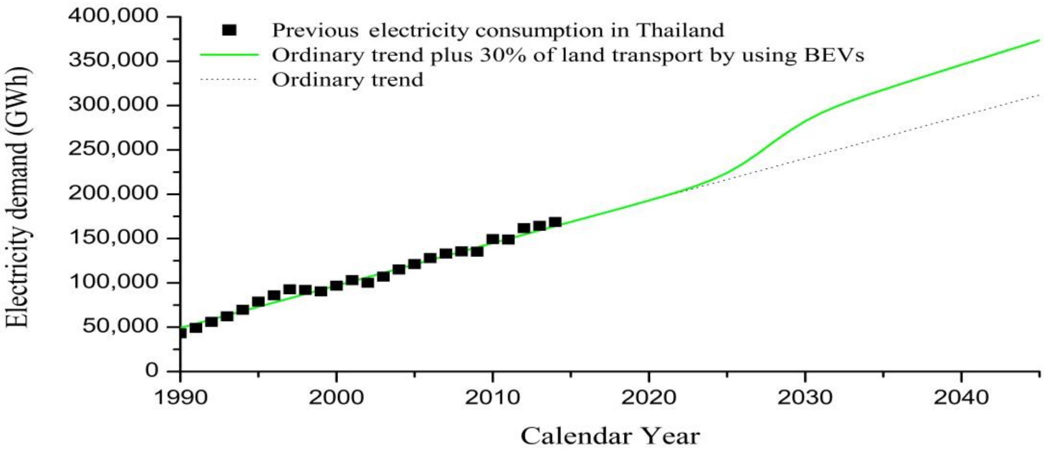

Figure 4 Trend in electricity demand in Thailand considering the impact of the transport sector

Step in finding the trend of overall electricity demand is shown in Figure 3. The trend line for the overall electricity demand, including those that have been used for BEVs for transport sector, is represented in the green line that shown in Figure 4. The adoption of BEVs as 30% of the land transport sector in 2035 will increase the total electricity demand more than the ordinary trend for approximately 12%.

3.3 Risk from fuel oil crisis

The electricity demand, as presented by the green curve, considered the period in which some ICVs will be replaced by BEVs; this is an important period. We observed that the impact of BEVs electricity demand will be sufficiently large to change the previous trend. Neither the beginning nor the end of this period is a fixed point. Both of these points may shift closer or farther apart based on many factors such as the oil situation, the BEV price and tariff. Short period means rapid increase in electricity demand. At present a BEV and its maintenance cost may be higher than an ICV. However, the use of electric vehicles must not be discouraged. Because this will push the beginning time further long while the ending time of transition is limited by time of oil depletion. If fuel oil crisis is happened and enough strong to cause the cost of an ICV higher than or close to a BEV then rapidly increasing of BEVs may follow. In opposite, if BEVs are too much promoted then a rapid increase of power demand may happen also. A way to reduce the risk is the attempt to expand transition period as much as possible. Another way is to support multiple form of energy consumption such as supporting hydrogen fuel cell vehicles or bio-fuel vehicles, etc.

4. CONCLUSION

To replace ICVs by BEVs, the electricity demand from power distribution system can be estimated by considering the amount of past fuels use by ICVs, which the effect from traffic condition, vehicle load and the incline of the route had collected in the fuel consumption. To replace ICVs by BEVs, every 1,000 ktoe of fossil fuel used must be compensated by 3,510 GWh of electricity. In the case that 30% of the land transport sector in Thailand will be BEVs in 2035, overall electricity demand will higher than the ordinary trend by 12%.

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