Single and Multi-sources Energy Sizing for Electric Vehicle: A Case Study

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***Abstract*—The automotive industry has introduced various renewable-energy based technologies such as battery electric vehicles (BEV) and fuel-cell electric vehicles (FCEV). However the main concern is addressing issues to determine which vehicle with different energy sources are more efficiency and cost saving than the others. In order to overcome this issue detailed analysis need to be performed on the important criterions in vehicle sizing like energy cost, dissipated energy and effective energy source (EES). This paper deals with the modeling, evaluation and analysis of single and multi-source electric vehicle (EV) on three classes of EV, namely the light electric vehicle (LEV), medium electric vehicle (MEV) and electric vehicle (EV). A comparison on dissipated energy with different EES, charging cost and weight were made based on a linear mathematical calculation. The results have shown that multi-sources energy powered-vehicle deliver among the best dissipated energy and EES percentage. Findings of this energy sizing under various combination of EV would be helpful for further research on the EV energy applications.**

***Index Terms*—Sizing, Electric Vehicle, fuel cell, super-capacitors, battery.**

I. Introduction

People's increased awareness to reduce negative environmental impact has shifted automotive technology from using pure internal combustion engine (ICE) into combining it with one or more sustainable energy resources, and this is commonly referred to as the HEV or multi-source EV (MSEV). Statistics have shown that transportation consumes almost one third of total energy consumption in the world and produces greenhouse gases (GHG) of about 33.7% in year 2012 [1-2]. According to Andersen et al. [3], the usage of HEV is estimated to reduce GHG to 20% and it can even be reduced further to 40% in the case the power generated originates from a renewable energy source too.

Based on the energy efficiency, electric motor vehicle is the best since about 60-75% of its energy is used to drive the vehicle and the rest is a loss due to friction. On the other hand, for the ICE vehicle, 70% of energy goes into heat loss when converting thermal energy to kinetic energy and another 15% is lost due to friction. Effectively, the ICE only uses 15% of its energy to drive the vehicle. Therefore, when both systems are combined, the expected energy efficiency lies between 15-75% [4].

Since no complex equation is involved, this paper proposed a linear mathematical method in sizing of energy sources for the various EV applications [5-6]. One of the focus types of EV is the MSEV. It combines three energy sources, namely the battery, fuel cell (FC) and ultra-capacitor (UC). Then in terms of weight, dissipated energy and cost of the vehicle will be presented and compared with single energy source EV as well as battery electric vehicle with solar (BEV + solar). Their differences will then be discussed in detail. The architecture of the designed model will be presented followed by the energy sizing of single energy source EV, battery electric vehicle with solar (BEV-solar) and the proposed MSEV. Then a comparison between those EV will also be discussed.

II. Parameters for Vehicle Sizing Model

All-electric vehicle (AEV) is the term used to describe a vehicle, which uses electric power source only. On the other hand, as their name suggests, Battery Electric Vehicle (BEV) and Fuel cell Vehicle (FCV or FCEV) use battery only or FC only as their source of power. These are the two types EV that automaker mostly invested in. BEV or Plug-in BEV is already available in the market in car model such as Tesla, Nissan Leaf and Mitsubishi iMiev [7-8]. Meanwhile, FCV is still at the prototype stage with prototype model like Honda FCV.

EV is classified by weight. EV with weight greater than 1000 kg is considered as four-seated electric vehicle (EV), whereas EV with weight between 400-800 kg is considered as two-seated EV or medium EV (MEV). The third class of EV is known as Light EV (LEV) with weight less than 400 kg. In order to measure dissipated energy, energy cycle test is performed. Test is conducted by comparing specific distance and speed according to different energy sources and their EV classes. The summary is presented in Table 1. The total force, F_t is calculated according to vehicle characteristics as shown in Table 2 through the equation below [9-10]:

$$F_t = \mu_{rr} mg\cos(x) + \frac{1}{2}\rho \cdot A \cdot C_d v^2 \qquad (1)$$

Table 1
Specification of various energy sources [1-6]

Energy Storage/Source Type	Specific Energy (Wh/kg)	Specific Power (W/kg)	Life cycle	Energy efficiency (%)	Charge efficiency (%)	Cost (RM/Wh)	Recharge Time
Lead- Acid	30-40	180	800	>80	>85	0.35	> 6 hour
Ni-Cad	50-80	200	2000	75	>90	3.80	> 2 hour
Ni-MH	70-95	200-300	<3000	70	>90	3.90	> 4 hour
Li-ion	120-200	200-430	2000	>90	>90	9	> 1 hour
Ultra-capacitor	5-7	1-2M	500,000	>95	>95	300	> 10 min
Hydrogen + Fuel Cells	300-3000	1-100	<10000h*	<60	-	0.00020**	< 15 min
Petrol (RON 97)	12,700	-	1	<30	-	0.000025**	< 5 min

* Fuel cell Stack in hours, ** Hydrogen cost only, *** Petrol cost only

where g is the earth gravity 9.81 ms-1, v is the vehicle velocity, ρ is the air density 1.25 kgm-3 and cos (x) is 1 (no slope condition). Then, the sum of energy used for EV, ΔE, is calculated from the total force and travelling distance, *D*, and includes the energy source efficiency, ηee, and motor and vehicle efficiency, ηme. The applied equation is:

$$\Delta E = \frac{Ft \cdot D}{\eta_{me}\eta_{ee}} x\left(\frac{1h}{3600s}\right) \quad (2)$$

Table 2
Vehicle characteristics and parameters [1-6]

Type of EV	LEV	MEV	EV
Rolling Resistance Coefficient μ_{rr}	0.01	0.014	0.018
Frontal Area, A [m^2]	1.0	2.0	2.5
Drag Coefficient, C_d	0.75	0.32	0.35
Vehicle constant speed, v [kmh^{-1}]	50	70	90
Motor Efficiency, η_{me} [%]	70	70	70
Energy Efficiency (Ni-Cad)*, η_{ee} [%]	75	75	75
Distance, D [km]	80	120	160
Vehicle Weight**, *m* [kg]	180	500	1000
Dissipated Energy **, ΔE [kWh]	3.4	10.5	33.1

* Refer to table 1 for other energy sources efficiency
** Without consider weight of the energy sources

Effective energy source (*EES*) is calculated in percentage from the proportion of the dissipated energy of EV. There are two kinds of *EES* values – E_{woes} which does not take energy source weight into account, whereas E_{wes} does. The following equation shows the relationship between both *EES* parameters:

$$EES = \frac{E_{woes}}{E_{wes}} x100\% \quad (3)$$

By introducing *EES*, the efficiency of an energy source in EV application can be seen according to their classes. The *EES* value can be used to determine possible combination of various sources in sizing multi-sources EV.

The focus of this research is to study the dissipated energy, cost and effectiveness of renewable energy sources. The dissipated energy is modeled after equation 1 and 2 with the characteristics of vehicle as shown in Table 2. The *EES* is introduced in equation 3 to indicate the effectiveness of each energy sources. The estimation cost of each energy sources is made based on the Malaysian market.

III. RESULT AND DISCUSSION

In total, there are five different electric vehicle systems being analyzed. They are the battery EV (BEV), fuel cell EV (FCV), ultra-capacitor EV (UCV), battery with solar EV and multi-sources EV that combine the battery, fuel cell and ultra-capacitor as its energy sources. As mentioned before, three different vehicle weight classes, namely the light (LEV), medium (MEV) and normal (EV), will be evaluated accordingly. An evaluation is made based on the energy source's physical weight, expense for first purchase, cost to recharge, dissipated energy ratio and effective energy source. For the measurement of the dissipated energy, the vehicle is configured with constant load condition. Detailed analysis descriptions are described in the following five sub-sections. Subsequently, an evaluation comparison of all tested systems is presented.

A. BEV Energy Sizing

The first electric vehicles invented in the 1830s used non-rechargeable batteries [11-12]. But in the 1920s, after cheap gasoline was widely available and the self-starter for ICE was invented, ICE engines start dominating the sector. In the early 1960s-1970s, the EVs appear again but in small numbers. Today, BEV production is increasing after the lead acid battery was replaced by Li-ion battery. The contribution factor for the replacement is actually the weight of the lead acid battery itself. For example, the weight of lead acid in an EV (1000kg) is half of the vehicle weight. In comparison to the Li-ion battery, it is three times less weight than the lead acid. The evaluation of Li-ion battery in different EV classes such as battery light EV (BLEV), battery medium EV (BMEV) and BEV can be seen in Table 3.

Table 3
Evaluation of Li-ion battery in different EV classes

Vehicle Class	BLEV	BMEV	BEV
Li-ion Battery			
Battery Weight [kg]	17.2	52.7	165.7
Battery Starting cost [RM]	39330	$1.2x10^5$	$4.2x10^5$
Battery Charging cost [RM]	0.95	2.95	9.40
Dissipated Energy including battery weight [kWh]	3.9	12.1	38.9
Effective energy sources, EES [%]	88.6	87.6	85.1

The *ESS* for the Li-ion batteries, as shown in Table 3, is excellent for all classes, with the average of more than 85%. This is due to the fact that Li-ion battery is capable to hold outstanding specific energy. However, the cost of Li-ion batteries for EV commercialization is so high that it is not favorable for consumers from the normal class income. Such BLEV will cost RM 40 000 with Li-ion battery, whereas the same vehicle will cost RM 1500 if lead acid battery is used. Nonetheless, the price of Li-ion batteries is projected to reduce by 30% in 2020.

The charging cost calculation of Li-ion batteries is made based on the amount of energy needed for full recharge, charging efficiency and electricity price of RM 0.218 per kWh, as charged by Malaysian electricity provider, Tenaga Nasional Berhad (TNB, Rate 2011). The Li-ion has a charge rate at RM 9.40 for EV with the amount of energy required is 43.2 kWh from the grid. Thus, the charge cost expected for a standard car will be RM 20 to cover a 160 km journey. This also means that BEV charging saves 30% of the traveling cost if powered by ICE.

B. FCEV Energy Sizing

Unlike the battery, fuel cell works via energy conversion and not energy storage. Hydrogen stored in the storage tank will then be fed into FC to create electricity. In FC energy sizing, weight of the FC and storage tank are considered in the *EES* calculation. In the market, the size of a smaller storage tank is more expensive than the standard tank size for EV. FC power rate is calculated as half of the dissipated energy needed because an extended distance traveled would mean that a larger storage tank is required, see Table 4. The evaluation stands in light FC EV (FCLEV), medium FC EV (FCMEV) and standard auto size FC EV (FCEV).

Table 4
Evaluation of electric vehicle classes for FC

Vehicle Class	FCLEV	FCMEV	FCEV
Fuel Cell (PEM)			
FC power rated [kW]	3	10	30
FC stack and storage tank weight [kg]	70	140	250
FCs system starting cost [RM]	45000	$1.0x10^5$	$1.5x10^5$
Hydrogen refueling cost [RM]	1-2	4-6	12-18
Dissipated Energy including FC stack and storage tank weight [kWh]	6.1	19.1	60
Effective energy sources, EES [%]	56.4	55.1	55.2

FCs technology is rare in Malaysia and therefore, all components need to be imported. Additionally, the use of precious metal catalyst like platinum in FC stack has contributed to the high cost. The mentioned price is a prototype price, and it would be reduced if the vehicle is commercialized and it can even be reduced more if components are to be manufactured locally. The price of FCLEV is estimated around RM 45 000, whereas its conventional ICE equivalent will cost between RM 4000-6000. For an FCEV, estimated price is RM150 000, and its ICE equivalent cost about RM 40 000 – 60 000. This clearly shows that FCLEV powered by FC will not give high value money to consumers. In term of EES, FCEV returns slightly better value at 55% as compared to FCMEV and FCLEV. This is an acceptable value for FCEV class. However, if the vehicle is built with less power but large storage tank, it would be possible to improve the EES ratio.

Until today, there is no commercial hydrogen refueling station being built. Firstly, it is due to the fact that it requires huge investment and secondly, it will definitely increase the hydrogen market price once such setup exists. Thus, the estimation of hydrogen refueling cost will be 50% higher from the market price.

C. UCV Energy Sizing

UC is heavier than the battery with the same specific energy. Its weight could easily be one third of the whole vehicle volume. This results in tremendously low *EES* percentage when applied to MEV and EV. Consequently, the cost of EV powered by single UC could easily reach millions and is thus affordable only for rich people.

Even if UC can be designed to power a small sized LEV that can supply specific power of less than 10Wh, its voltage during discharge is inconsistent. Besides, its output voltage will drop linearly with the energy capacity and this will require additional DC-DC converter to maintain consistent voltage supply. In the normal practice, only half of the energy will be used before it will need to be recharged again. The evaluation for UC powered EV (UCEV), UC powered MEV (UCMEV) and UC powered LEV (UCLEV) is presented in Table 5.

Table 5
Evaluation of electric vehicle classes for UC

Vehicle Class	UCLEV	UCMEV	UCEV
Ultra –capacitor, UC			
UC Weight [kg]	491.6	1504.7	4732
UC Starting cost [RM]	> RM millions	> RM millions	> RM millions
UC Charging cost [RM]	1.20	4.95	21.05
Dissipated Energy including UC weight [kWh]	5.3	21.6	91.8
Effective energy sources, EES [%]	65.4	48.7	36.1

The present technology still limits the usage of UC as a primary energy storage for an EV. However, it is advantageous to be used as FC-energy-supporter due to its significant specific power. Therefore, it is common to couple FC with UC in vehicular applications to provide better energy efficiency, steady state and peak power necessity. UC can be charged during regenerative braking and discharge to support load demand frequently, even in a fraction of second. This happened with almost no effect to cycle capability or loss in dynamic behavior.

D. BEV with Solar Energy Sizing

Having solar panel on top of an EV is quite a smart idea if travelling is planned accordingly to harvest maximum amount of solar energy. However, solar cannot be made as the primary energy source due to inconsistency and uncertainty in weather condition. This is true even in tropical country like Malaysia since weather can just instantly change its face from sunny side to a stormy heavy rain, which could have high impact on the solar radiation dependency. Therefore, battery needs to be coupled with solar panel, where battery will be the primary energy source and the latter will be the secondary energy source.

The charging expenses for BEV with solar panel will be slightly higher than BEV because of the additional load of the solar panel on the vehicle. In this study, power generated by the solar panel is not taken into account because it relies on how effective can the user utilize this renewable energy. If between 1-2% of energy comes from solar harvesting, the charging cost can be reduced and part of the dissipated energy can be covered by solar energy. This will in return increase EES value.

Within this solar EV energy sizing, evaluation of the dissipated energy and EES is made with Li-ion battery. The EES value for this system reduced slightly 1-2% to 86.1% for BLEV, 85.1% for BMEV and 83.4% for BEV. Complete evaluation result is shown in Table 6.

Table 6
Evaluation of BEV with solar panel

Vehicle Class	BLEV + solar	BMEV + solar	BEV + solar
Solar + Battery (Li-ion)			
Solar panel area [m2]	1.2	2.8	4.4
Battery and Solar panel Weight [kg]	36	90	228
Battery and Solar panel starting cost [RM]	42000	128445	425251
Battery Charging cost [RM]	0.96	3	9.6
Dissipated Energy including Battery and Solar panel weight [kWh]	4	12.4	39.7
Effective energy sources, EES [%]	86.1	85.1	83.4

E. Multi-sources EV (MSEV) in energy sizing

In this system, three energy sources namely Li-ion battery, FC and UC are combined. FC acts as a primary energy source and covers 60% of vehicle capacity. Li-ion battery on the other hand will support almost 40% of vehicle capacity and UC will contribute 0.5% to the energy sources. The evaluation of the energy sizing is presented in Table 7. The *EES* values measured is an average of more than 60% for all vehicle classes. Since FC and Li-ion are both expensive, production of such a vehicle will surely be costly. The combination of 60% of FC and 40% of Li-ion battery is to give more opportunity for the consumer to choose either to recharge battery or refueling FC.

Table 7
Evaluation of Multi-sources EV

Vehicle Class	MSLEV	MSMEV	MSEV
Battery (Li-ion) + Fuel Cell (PEM) + UC; Multi-sources (MS)			
FC stack and storage tank + battery + UC weight [kg]	45	100	260.8
Multi-source system starting cost [RM]	40000	1.2×10^5	3.0×10^5
Charging and refueling cost [RM]	1.5	4.6	14.5
Dissipated Energy Multi-source system [kWh]	5.1	16	52.2
Effective energy sources, EES [%]	67.0	65.7	63.5

IV. Comparison Energy Sizing of Different Vehicle Classes

The following discussion is about comparison of the result from selected Table 3-7. Figure 1-3, shows a comparison of energy source weight, starting cost, charging and refueling cost and *EES* of three types of EV classes. The evaluated EV systems vary from using single energy resource such as battery, FC, FC + solar or multi-sources energy that combines battery, FC and UC. The expenditure study applied to Malaysian market and thus may differ from other countries. The comparison does not take into account of self-discharge degradation, life cycle and temperature impact.

In term of weight for LEV class in the Figure 1, FCLEV is the heaviest at 70 kg due to its storage tank and FC stack load, followed by MS- LEV at 45kg. BLEV + solar only weights the half of FCLEV whereas Li-ion LEV only weights one quarter of FCLEV.

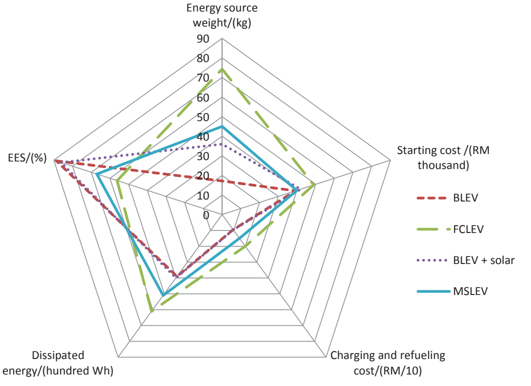

Figure 1: Evaluation of LEV energy sizing

The starting cost for FCLEV is the most expensive at about RM 50000. MSLEV needs almost the same cost as BLEV and BLEV + solar of RM 40000. In MS-LEV, a 2 kWh FC stack can be used rather than 3-4 kW for FCLEV. For additional power, a combination of Li-ion battery can be implemented.

Regarding charging and refueling cost, battery-powered vehicles are the most economical at the cost of RM 1 per full charge, followed by MSLEV at RM 1.50 and FCV at RM 2. System with the most dissipated energy is FCLEV at 6kWh and the least dissipated energy are BLEV and BLEV + solar with value at 4kWh. Since the EES and dissipated energy value is inversely related, the most efficient LEV will have the least dissipated energy. Thus, BLEV and BLEV + solar shows excellent efficiency with *EES* value greater than 85%. MSLEV has the value of above 60%, whereas FCLEV value is at 56%.

For medium class EV in the Figure 2, FCMEV is the heaviest at 150kg, followed by MS-MEV at 100kg. The combination of 40% of Li-ion battery in MSMEV has made this vehicle lighter than FCMEV. Next, the BMEV + solar is weight at 90 kg and BMEV is at 50 kg.

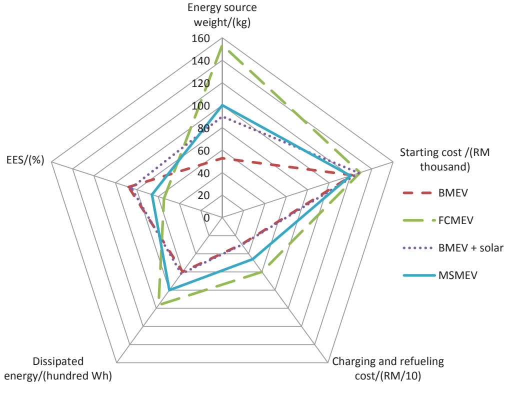

Figure 2: Evaluation of MEV energy sizing

The use of Li-ion battery in MSMEV caused its starting cost margin to be much higher as compared to MSLEV. It could reach up to RM 122 000 and nearly match the cost of FCMEV, BLMEV and BLMEV + solar at RM 130 000.

Charging/refueling cost of MS-MEV is RM 4.60, and it is smaller than FCMEV, which has the value of RM 6. As already mentioned, the estimation price for hydrogen might be slightly higher if refueling station and higher hydrogen production cost is taken into consideration. The rest of the energy sources have recharging cost in the range of RM 3.

FCMEV consumed the highest dissipated energy of about 19 kWh, followed closely by MSMEV with the value at 16 kWh. The BLMEV and BLMEV + solar on the other hand have burn-up energy at the same rate of 12 kWh. The *EES* rate for BLMEV and BLMEV + solar is more at 85%, whereas MSMEV and FCMEV have the rate of 60% and 55% respectively.

Energy sizing for the proposed energy cycle in normal EV is more than 30kWh, see Figure 3. Thus, in order to achieve the proposed energy amount, the equivalent FCEV will weigh about 290 kg. This is followed by MS-EV with 260 kg. Since Li-ion battery has high specific energy, BLEV and BLEV + solar weight will be at 165kg and 228kg respectively.

Although it is low in weight, Li-ion battery is still costly for commercialization purposes. It will cost more than RM 420 000 to design EV that has energy capacity 30kWh. The MSEV will significantly reduce the price to RM 300 000. For FCEV, it costs about RM 240 000.

In terms of charging/refueling, battery powered EV proved the lowest cost for all vehicle classes. In the normal EV energy cycle, FCEV required the most dissipated energy at 60 kWh. Next, it follows by MSEV at the range of 50kWh, then BLEV and BLEV + solar at 38kWh. In term of efficiency, BLEV and BLEV + solar are the top two with 80% of EES. This is followed by MSEV at 60% of EES. FCV is the lowest with EES of 55%.

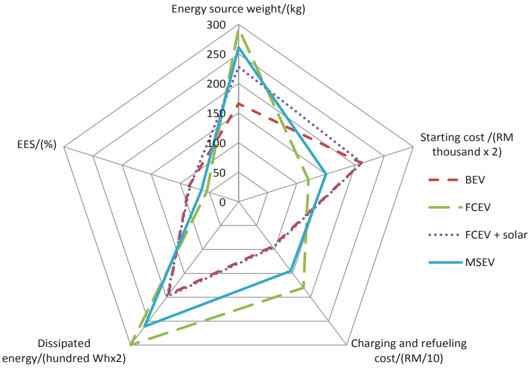

Figure 3: Evaluation of EV energy sizing

In general, BEV has better performance in all specification criteria but its starting cost is high and it can rise exponentially with vehicle weight. On the other hand, although it is the best choice, battery BEV requires long charging time but this factor is not valued in this comparison study. This is the main drawback that moves the automotive industry players to look for an alternative like FCEV. FCEV can actually offer short refueling time of less than 10 minutes if proper FC refueling infrastructure is built [13-16]. However, from this comparison study, all classes of FCEV have always the worst value in many operation aspects such as *EES* and starting cost. Since every energy source has its own advantages and disadvantages, as a result, a multi-sources EV is introduced to put an average on these criteria and build EV with fair performance and efficiency. The system can take advantage of the powerful and light weight BEV and shorter refuel time of an FCEV. In fact, consumer has options between recharging battery and refueling hydrogen.

From all three graphs shown in Figure 1-3, it can be concluded that in general, MSEV classes criteria value always lie in between the value of BEV and FCEV classes. Therefore, a MSEV delivers the average performance value of BEV and FCEV.

V. Conclusion

From the study and test performed, it can be seen that MSEV delivers an averaged advantages from both BEV and FCEV for all considered criteria in all EV classes except for starting cost. On the other hand, this combination also enables single energy's drawback to be straightening up by the other party. As an example, with the FC inside the system, refueling duration can be shortened as compared to a single BEV.

Such a system also enables the introduction of an intelligent controller to manage the energy sources to better respond to different vehicle load and driving condition. This allows more flexibility into the system and improves energy efficiency significantly. Furthermore this MSEV will also introduce a new fuel type to consumer – hydrogen. This also opens up a lot of research possibilities in working on the efficient way to refuel without the need to build billion dollars' worth of refuel station.

The marketability of such MSLEV in Malaysian market is hard to predict due to quite high starting cost. However, if more components can be arranged to be produced locally, this will surely reduce the cost and invite more middle income consumer to switch from conventional ICE engine to an environment friendlier equivalent – the MSLEV.

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