Implementations of Electric Vehicle System Based on Solar Energy in Singapore Assessment of Lithium Ion Batteries for Automobiles

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Implementations of Electric Vehicle System Based on Solar Energy in Singapore
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ABSTRACT

In this thesis report, both quantitative and qualitative approaches are used to provide a comprehensive analysis of lithium ion (Li-ion) batteries for plug-in hybrid electric vehicle (PHEV) and battery electric vehicle (BEV) from technological and economical perspectives. Five key factors including power density, energy density, safety, durability, and cost are employed to compare four types of Li-ion batteries. Utility analysis indicates that all the Li-ion batteries are able to satisfy both power density and energy density targets, but only two of them are able to meet safety and durability requirements. Currently, the main challenge for their automotive application is cost reduction, since the cheapest $LiFePO_4$ battery costs $247.8/kWh which is 1.65 times the cost target established by USABC. Economical values of PHEV and BEV are presented from an end user's point of view. Various sensitivity analysis have been used to identify the impact of key factors such as battery pack cost reduction, driving distance, gasoline price, and government subsidizations on cost effectiveness of PHEV and BEV. Results show that $4,270 and $7,726 of U.S. government subsidizations to an individual user are needed for PHEV and BEV to breakeven.

Lastly, the lithium ion battery based electric vehicle systems have also been evaluated in the implementation models in Singapore. The conclusion is that it is not feasible to adopt electric vehicle system in Singapore under current government incentives.

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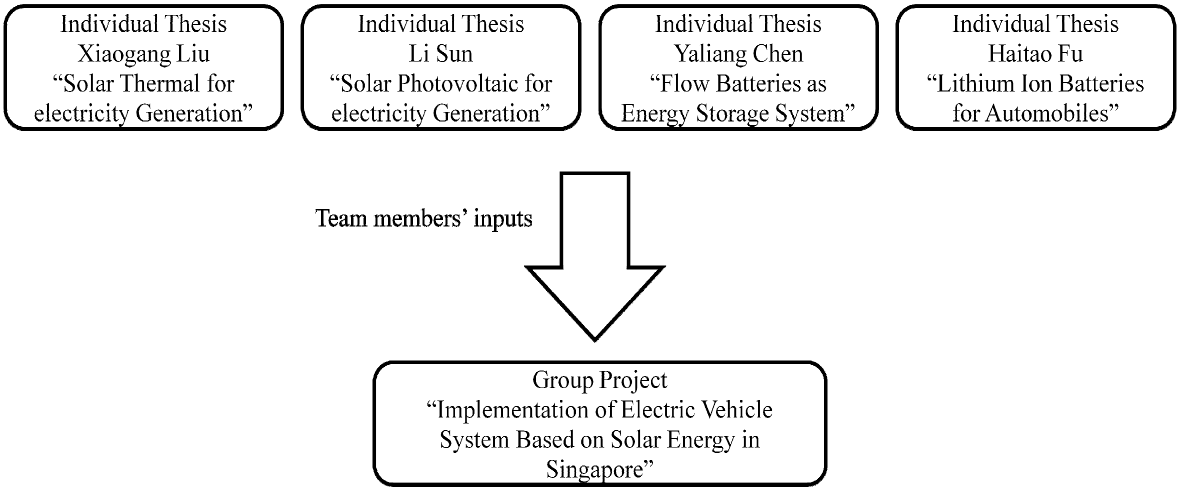
LCO	Lithium cobalt oxide
LMO	Lithium manganese oxide
LFP	Lithium iron phosphate
NCM	Lithium nickel cobalt manganese oxide

Motivation of Study

Preface

This report serves as a constituent part of the group project "Implementation of Electric Vehicle System Based on Solar Energy in Singapore" shown in the project structure below. It is an independent thesis work on technological and economical assessment of lithium ion batteries for automobiles. The rest of team members' individual theses can be retrieved from MIT library archives for references.

Project Structure



Background

Singapore, as one of the cleanest countries in the world, has formally acceded to the Kyoto Protocol on July 11th, 2006. According to Singapore National Climate Change Committee, from 2012 to 2016, Singapore has set the target to lower its CO_2 emission below the level in 1990[1]. In order to achieve this standard, Singapore government has initiated a series of acts such as using highly efficient combined cycle gas turbine, replacing crude oil with natural gas as the major source for power generation and promoting public transportation. Recent development of green vehicles such as electric vehicles has indicated that a sustainable transportation system needs to be employed to effectively achieve CO_2 reduction. With reduced CO_2 emission and operation cost, electric vehicles offer both environmental and economic values to Singapore. According to Mr Lawrence Wong, Chief Executive of Energy Market Authority, Singapore is considered to be well suited for electric vehicle implementation for its small size, robust electric grid, and advanced IT services. This has created an ideal infrastructure for electric vehicles. Furthermore, as a tropical island country located near to the Equator, Singapore has abundant solar radiation throughout the year. Solar energy has been identified as the first alternative to fossil fuel in Singapore. And Singapore government is committed to promote solar industry in the country for the next a few decades[2].

Objective

The objective of this thesis report on is to characterize different types of lithium ion batteries as energy storage for electric vehicles. In particular, 5 factors will be taken into account for the evaluation: power density, energy density, safety, durability, and cost. The objective of the group project is to analyze a sustainable transport system based on electric vehicles and solar energy in Singapore. Results obtained in this thesis report on assessment of lithium ion batteries in automobiles will be evaluated in Singapore context in the group project.

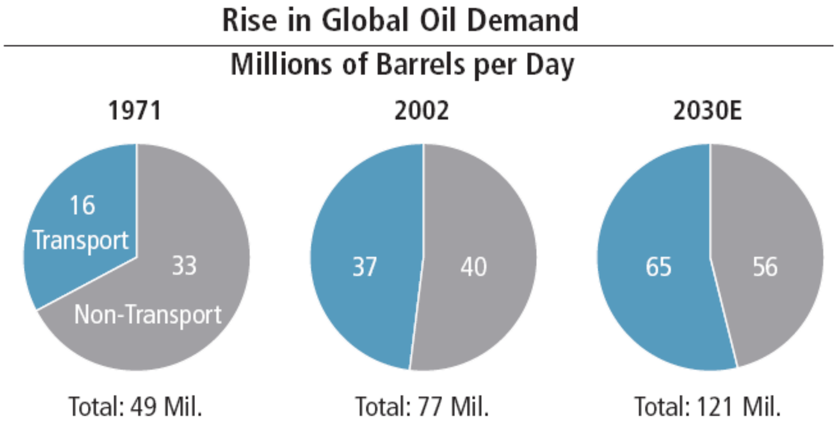
Report structure

Chapter 1 to chapter 5 will discuss assessment of lithium ion batteries for automobiles. The group project is presented in chapter 6.

Chapter 1 provides an overview of energy storage systems. Chapter 2 describes lithium ion batteries and their electrochemical performances. Chapter 3 focuses on the market analysis of electric vehicles and lithium ion batteries. Cost model, manufacturing strategy, utility analysis, and implementation effectiveness are discussed in chapter 5. In chapter 6, four implementation models will be discussed.

Chapter 1 Introduction

Demand for oil has driven its price to be more volatile than it was in the early 1990s[3]. According to the statistics provided by Alliance Bernstein, global oil consumption has increased by 131.25% in the past 3 decades, and it will further increase by 75.67% in next 30 years shown in Figure 1. With substitutions for oil in electricity generation such as nuclear and solar technologies, oil consumption has gradually shifted towards transportation. It is predicted by International Energy Agency (IEA) that oil consumption in transportation will dominate and exceed 50% of total oil consumption by end of 2030[4].



Sources: IEA, World Energy Outlook 2004 and AllianceBernstein

Figure 1 History of Oil Demand

As the green house gas (GHG) emission is causing global warming, and increasing fuel consumption in transportation sector is tightening the environmental tension. In US, transportation contributes more than 30% of its total Green House Gas (GHG) emission[5], while that in Singapore contributes 19% of its total GHG emission[6]. This figure is expected to boost further in near future. Therefore, both economical and environmental issues urge for a more fuel efficient gasoline vehicle. In response, people have been developing technologies such as variable valve timing & lift, and turbochargers & superchargers have been developed over past years to reduce transportation CO_2 emission. More recently, people start to realize that drastic evolution in automotive industry is needed to reduce oil consumption and transport related Green House Gas (GHG) emission. Therefore, interests have been focused on development of electric vehicles including hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), and battery electric vehicle (BEV).

The concept of electric vehicle was introduced during 19th century. Since then, people have been developing the technology for more than a century, yet no one has commercialized it successfully. An important reason for its under-performance compared with gasoline car is that the battery technology did not meet the specification[7]. Currently, various energy storage systems have been developed, and they are able to meet part of the energy storage targets established by US Advanced Battery Consortium (USABC), since none of them can meet all the targets simultaneously. As shown in Figure 2[5], ultracapacitors are able to provide higher power solutions, virtually unlimited life cycle, and extreme temperature tolerance, but their cost need to be lowered for automotive applications. Lead-Acid (PbA) battery has low power and energy densities. In addition, lead smelter can cause severe environmental problems if the battery is disposed improperly. Thus, NiMH battery has been used to replace PbA battery, and it is has been commercialized mainly in HEV. It has been proven to provide reliable power for HEV with an affordable price. However, there are several limitations with this battery. It has a low energy conversion efficiency that results in severe energy loss in the form of heat during usage. Meanwhile, capacity loss is observed if the battery is subject to wide State of Charge (SoC) window. To maintain capacity over its life time, only small portion of stored energy can be used during cycling. In addition, its bulky size, heavy weight, and high cost will further restrain its commercialization in electric vehicles especially PHEV and BEV[8].

Gradually, focus has been shifted towards lithium ion (Li-Ion) battery. Compared with ultracapacitor and NiMH batteries, Li-Ion battery can provide higher power and energy densities in combination with relatively low cost. What is more, unlike NiMH battery that has been subject to fundamental limits, there is still plenty of room for Li-Ion battery to improve. Figure 3 shows Li-Ion battery technology roadmap from early 1990s to 2001. In 10 years, Li-Ion battery has shown a significant improvement in energy density. In fact, various methods such as modifying cathode surface[9, 10], synthesizing single phase cathode materials[11, 12], and doping cathode with metals cations[13] have been proposed to further improve its performance.

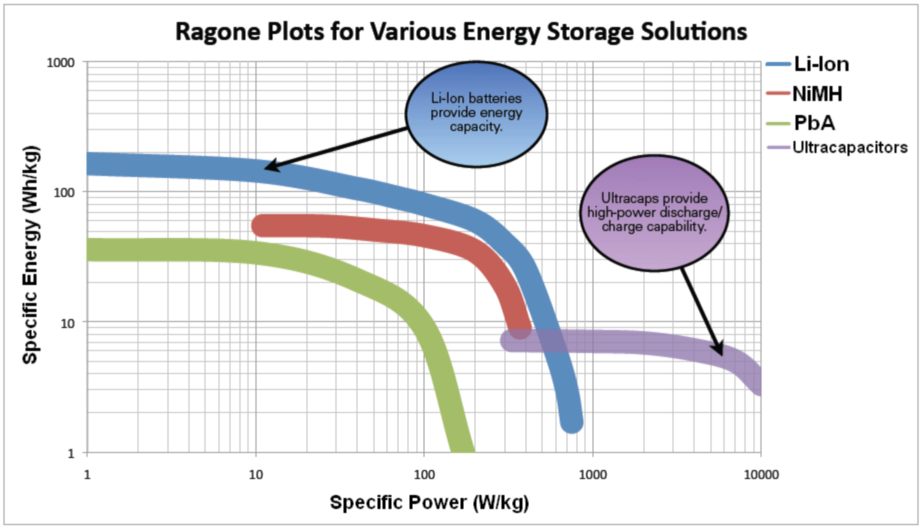


Figure 2 Overview of Energy Storage System

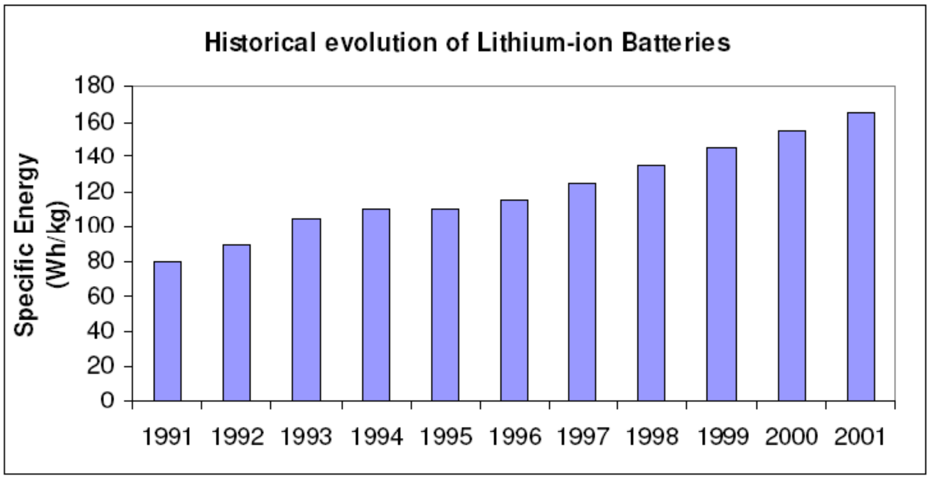
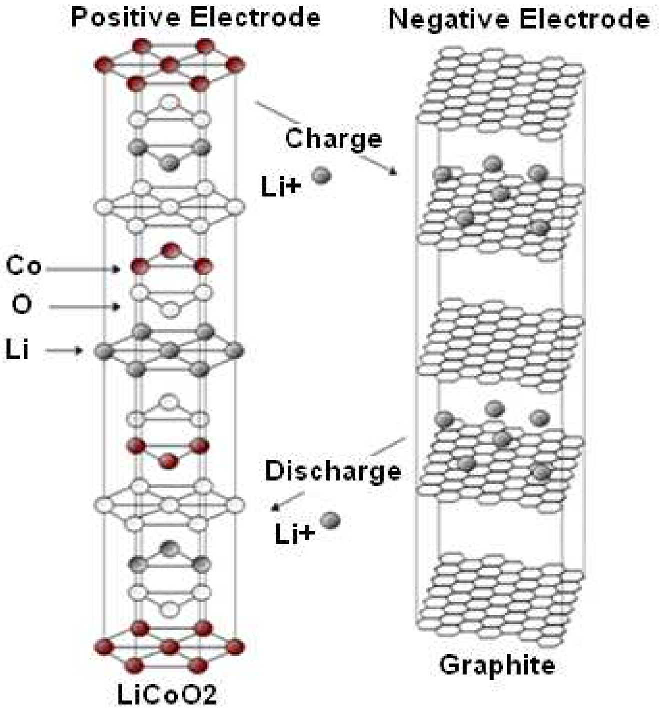


Figure 3 Historical Change of Li-Ion Battery

Chapter 2 Lithium Ion Battery Technological Assessment

2.1 Overview

In Li-Ion battery, the primary functional components are cathode, anode and electrolyte. During charging process, cathode compound will decompose to generate lithium ions, and lithium ions will move towards anode and then react with anode to form anode compound. In discharging process, anode compound will decompose and lithium ions will move back to form original compound. Figure 4 demonstrates the working mechanism of $LiCoO_2$ battery, for other Li-ion batteries, similar processes take place during cycling[14].



Cathode Reaction:

$LiCoO_2 \rightleftarrows Li_{1-x}CoO_2+xLi^++xe^-$

Anode Reaction:

$xLi^++xe^-+C \rightleftarrows Li_xC$

Overall:

$LiCoO_2 + C \leftrightarrows Li_{1-x}CoO_2 + CLi_x$

Figure 4 Working Mechanism of $LiCoO_2$ Battery

The voltage difference between cathode and anode is related to the Gibbs free energy in chemical reaction by the Nernst equation[15]:

$$\Delta G^0 = -nF\Delta E$$

ΔG^0: Gibbs free energy change in reaction

n: number of electrons involved in reaction

F: Faraday’s Constant

ΔE: electrical potential

Equation 1 Nernst Equation

Thus if given the battery voltage, current, and discharge time, its capacity and energy can be expressed as[16]:

$$C_p = \mathbf{I} \times \Delta \mathbf{t}$$

$$E = \int_0^t U(t) \times I(t) \times dt$$

C_p: Li-Ion battery capacity (Farads or Ampere hour)

I: battery current (Ampere)

E: energy stored in battery (joules or Watt hour)

U: battery voltage (Volt)

Equation 2 Battery Capacity and Energy

In general, there are 5 factors which are important in evaluation of Li-ion batteries for automotive application: power density, energy density, safety, durability, and cost.

Power density measures the speed of energy that can be extracted from storage system per unit mass. Battery must be able to provide an adequate amount of power since it determines acceleration and torque of the electric vehicle.

Energy density measures the amount of energy that can be stored per unit mass. For PHEV and BEV applications, energy density is critical, because battery with high energy density is able to provide a long electric driving range within the weight and space constraint.

Power and energy densities are fundamentally limited by the materials used in battery cathode. Given a specific cathode, battery could be further optimized to deliver either high power or high energy. Usually high power density or high discharging rate is achieved by using a thin film electrode which enables a fast inserting or withdrawing lithium ions. On the other hand, high energy density can be achieved by a thicker electrode which is able to obtain more active materials[17]. By given the experimental results, battery power and energy densities can be calculated as follows:

$$\text{Energy density} = \text{Capacity density} \times \text{Voltage}$$

$$\text{Power density} = \text{Current density} \times \text{Voltage} = \frac{\text{Energy density}}{\text{Discharge time}}$$

Equation 3 Power and Energy Densities

In most literatures, C-rate is used to convert energy density to power density instead of discharging time. It measures the discharge rate relative to the battery maximum capacity density. For example, if a battery has 100mAh/g maximum capacity density, 1C rate will deplete a fully charged battery in 1 hour with discharge current 100mA. Similarly, C/2 rate will deplete a fully charged battery in 2 hours with discharge current 50mA/g; 5C rate will deplete a fully charged battery in 0.2 hours with discharge current 500mA/g and so on.

Safety is critical for battery applications in automotive industry. It includes battery thermal stability and response to overcharging and short circuit[18].

Durability is considered in terms of battery cycle-life in which battery needs to maintain ideally 80% of its initial capacity at end of the vehicle life time[19]. Cycle life time is limited mainly due to side reactions between electrodes and electrolyte. These reactions cause slow degradation of electrodes which result in capacity fading and further reduce battery power and energy densities. Cycle life time is a large function of reactivity of electrode and electrolyte. It can be measured by battery impedance growth and capacity loss after years of operation. In low power and low energy consumer electronics industry, to improve battery durability, operating Li-ion battery in a small State of Charge (SoC) window is commonly used. This means the battery is only partially charged and discharged during cycling. For battery used in automotive and power tool industries, this is no longer valid since high power and high energy are needed which requires battery to operate in a wide SoC window.

Cost of battery pack greatly affects the total cost for electric vehicles especially PHEV and BEV. It is reported that for an electric vehicle, 75% of its incremental cost is from the Li-Ion battery[19]. Hence, cost of the battery must be reduced for electric vehicles to be competitive with its gasoline counterpart.

Following sections will focus on assessing four primary Li-ion batteries in terms of power density, energy density, safety, durability, and cathode synthesis. Their cost models will be discussed in section 4.3.

2.1.1 Lithium Cobalt Oxide Battery

Lithium Cobalt Oxide ($LiCoO_2$) battery has been matured for a long time and mass commercialized in consumer electronics[19]. It was first invented by Mizushima, K. et al[20] in 1980 and commercialized by SONY using graphite anode in early 1990s[21]. The $LiCoO_2$ cathode has α-$NaFeO_2$ structure with oxygen in a cubic close-packed arrangement as shown in

Figure 4 above. The layered structure contains Li^+ and Co^{3+} ions in discrete layers between planes of closed-packed oxygen ions. During charging, lithium ions are completely removed from cathode, thus oxygen layers will rearrange to form a hexagonal close packing structure in the form of CoO_2. Normally, more than one phase is formed with various degrees of distortion at oxygen lattice during cycling.

(a) Power and Energy Densities

$LiCoO_2$ battery is able to deliver a reversible capacity of 140mAh/g which is much lower than its theoretical capacity 274mAh/g. Conventionally, to further enhance its capacity, increasing its charge cut-off voltage beyond 4.4V vs. Li is used. However, this leads to dissolution of Co^{4+} ions into electrolyte during delithiation process. In addition, the three block cubic close-packed $LiCoO_2$ structure converts to a one block hexagonal close-packed structure, and this will require the movement of oxygen layers transforming from ABCA to ABA stacking sequence. This transformation will significantly disrupt the structure. As a result, cathode impedance increases which will affect the battery cycle stability[22]. Therefore, new mechanisms have been proposed to further increase the battery performance.

i. Coating metal oxide on the surface of $LiCoO_2$ particles

This technique was introduced by Cho et al in 2001[23, 24]. It is reported that sol-gel coating of metal oxide such as Al_2O_3 and subsequent heat-treatment is able to improve cell capacity as well as cycling performance. The coated cathode maintains 94.11% of its initial capacity after 70 cycles at charge cut-off voltage of 4.4V and 0.5C (70mA/g) discharge rate.

According to the theory proposed by the group, a smaller lattice expansion during cycling can lead to a better capacity and cycling stability. In more detail, Al_2O_3 will react with $LiCoO_2$ to form a layer of $LiCo_{1-x}Al_xO_2$. This thin layer can suppress the expansion of $LiCoO_2$ particles during cycling. It is also found out that metal oxide coating can eliminate the cathode particle phase transition from hexagonal to monoclinic, thus further improve the capacity and cycle performance. Consequently, the new $LiCoO_2$ battery is able to achieve a 160mAh/g capacity with voltage ranging from 2.75V to 4.4V after 70 cycles at 0.5C discharge rate.

ii. Synthesizing fine nano $LiCoO_2$ particles

Single phase small-sized particles are always desired in cathode synthesis process. Decreasing the particle size will extend the cathode area and hence increase the electrode capacity. Unlike conventional solid-state synthesizing process, new method using sol-gel process with poly(ethylene oxide)-block-poly(propylene oxide)-block-poly(ethane oxide) (P123) as soft template was introduced by Wu et al in 2005[25]. By using this synthesis process, homogenous and uniform sized particles are produced without particle agglomeration. $LiCoO_2$ nanoparticles are able to provide an initial capacity of 149mAh/g with a stable plateau voltage at 3.9V during discharge.

Other methods include aluminum doping[26, 27] which is to replace part of the cobalt used in cathode by aluminum. Besides improvement in capacity, Al-doped $LiCoO_2$ battery also shows better thermal stability with reduced heat generation during cycling.

Power and Energy Densities Estimation

By applying Equation 3, power and energy densities for $LiCoO_2$ cathode are estimated based on the discharging curve obtained from Cho et al[28]. The results are shown in Table 1 (calculation details are shown in Appendix A). According to US patent 0292444[29], a high energy Li-ion battery cell typically contains 25% to 35% by weight of positive electrode storage compound. Hence, in the following discussion, 30% by weight of positive electrode is chosen to estimate power and energy densities for all the Li-ion battery cells. Power and energy densities for a complete $LiCoO_2$ cell are estimated in Table 2.

Discharge C-rate	Current (mA/g)	Voltage (V)	Capacity (mAh/g)	Power density (W/kg)	Energy density (Wh/kg)
C/10	16.5	4.1	165	67.65	676.5
2C	260	3.9	140	1092	546
4C	440	3.75	110	1760	440
7C	560	3.5	80	1960	280

Table 1 $LiCoO_2$ Cathode Power and Energy Densities

Discharge C-rate	Power density (W/kg)	Energy density (Wh/kg)
C/10	20.3	203
2C	328	164
4C	528	132
7C	588	84

Table 2 $LiCoO_2$ Battery Power and Energy Densities

(b) Safety

Safety is an intrinsic problem of $LiCoO_2$ cathode. Several exothermic reactions will occur when it is subject to extreme conditions such as overcharging and overheating. When the cobalt oxide compound is heated, highly oxidizing nature of $Co^{3+/4+}$ couple causes it to decompose rather than melt[30]. During decomposition process, oxygen is released and exothermic reaction takes place which will ignite flammable electrolyte and lithium. Subsequently, more heat is generated to ignite neighboring cells. This phenomenon is commonly referred to as “thermal runaway”[31]. It will not only irreversibly damage the cell and shorten the cell life time, but also cause explosions. Experimental results by Yabuuchi et al[32] have demonstrated that $LiCoO_2$ cathode undergoes exothermic reaction at 200℃.

To address this problem, over voltage switch and complicated protection circuits are embedded into $LiCoO_2$ battery pack in order to prevent overcharging as described in US patents 6046575[33].

Other alternative methods such as applying polyethylene (PE) separator have been proposed by Laman et al in 1993 to enhance battery safety without installing sophisticated protection circuits. PE separator will automatically shut down the current by closing its micropores once the temperature is above its melting temperature. Nevertheless, the study by Imachi et al[34] from Sanyo Electric Company have shown that this protection mechanism is potentially unstable, because PE separator will be torn by the heat generated during overcharging. Hence new protection mechanisms are under development to prevent battery from overcharging such as fire retardant additive proposed by Obrovac's group[35].

(c) Durability

The battery cycle life is limited due to decomposition of $LiCoO_2$ compound during cycling. By coating the cathode with metal oxide, battery capacity retention can reach above 90% after 70 cycles at C/2 discharge rate under room temperature. Whereas the uncoated $LiCoO_2$ battery suffers from severe capacity loss, it can achieve only 58% of its initial capacity after 30 cycles shown in Figure 5[24].

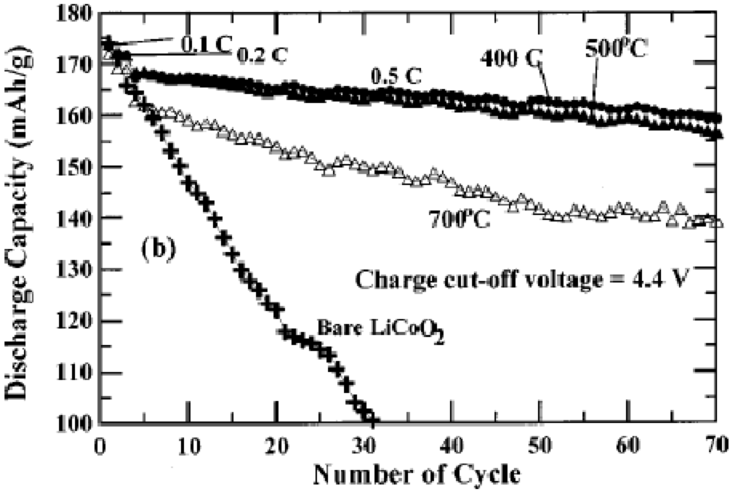


Figure 5 Metal Oxide Coated $LiCoO_2$ Battery Discharge and Cycle Curve

(d) Cathode synthesis

According to US Patent 6916580[36], the method of preparing $LiCoO_2$ cathode coated with a layer comprising two elements Zr and Al are shown in the following steps.

The coating liquid is prepared by mixing a 50wt% zirconium ethylhexanoisopropoxide suspension and 50wt% aluminum ethylhexanoisopropoxide in a volume ratio of 1:1. Then $LiCoO_2$ are mixed with coating liquid in a weight ratio of 50:50 in 50g of isopropanol. The coated $LiCoO_2$ are dried at 100°C for 2 hours and then heat treated at 400°C for 10 hours to form $LiCo_{1-a}Zr_bAl_cO_2$ ($0<a\leq0.6$, $0<b\leq0.2$, $0<c\leq0.2$).

2.1.2 Lithium Manganese Oxide Battery

Following the discovery of $LiCoO_2$ battery, Goodenough et al[37] invented Lithium Manganese Oxide ($LiMn_2O_4$) battery in the year 1983. In the following years, this cathode was extensively developed in Bellcore labs. In contrast to $LiCoO_2$ layered structure, $LiMn_2O_4$ cathode has a spinel 3-D structure as a cubic close packing of oxygen atoms. Manganese occupies half of the octahedral sites, where Li occupies eighth of the tetrahedral sites as displayed in Figure 6.

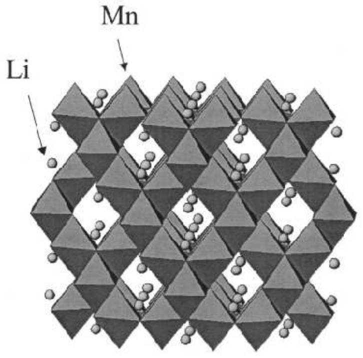


Figure 6 $LiMn_2O_4$ Spinel Structure

(a) Power and energy densities

With this kind of spinel structure, the framework is proven to be able to intercalate lithium ions reversibly at voltage 4.1V vs Li/Li^+ with theoretical capacity 148mAh/g. However, the practical capacity is found to be only 120mAh/g by Shin et al[38]. The relatively low practical capacity is due to the fact that not all the lithium ions are extracted during charging. By substituting metal cations such as Ni or Co for manganese, the capacity and rate capability were improved. In addition, it has also improved the capacity retention after cycles of operation and this will be discussed in detail in its durability section. By applying the same topology, power and energy densities for cathode and battery cell are estimated based on the discharging curve obtained from Shin et al. The results are shown in Table 3 and Table 4 (calculation details are shown in Appendix A).

Discharge C-rate	Current (mA/g)	Voltage (V)	Capacity (mAh/g)	Power density (W/kg)	Energy density (Wh/kg)
C/10	12	4	120	48	480
C/5	24	4	115	92	460
C/2	60	3.9	110	214.5	429
C	120	3.9	105	410	410
2C	240	3.8	100	760	380
4C	480	3.7	90	1332	333

Table 3 Metal Cation Substituted $LiMn_2O_4$ Cathode Power and Energy Densities

Discharge C-rate	Power density (W/kg)	Energy density (Wh/kg)
C/10	14.4	144
C/5	27.6	138
C/2	64.4	128.7
C	123	123
2C	228	114
4C	399.6	99.9

Table 4 Metal Substituted $LiMn_2O_4$ Battery Power and Energy Densities

(b) Safety

Compared to $LiCoO_2$ battery, $LiMn_2O_4$ has a much higher thermal stability. It was proven by Tobishima et al[39] that the exothermic reaction temperature of $LiMn_2O_4$ battery is higher than that of $LiCoO_2$ battery. Meanwhile, the heat output rate of $LiMn_2O_4$ is also lower than that of $LiCoO_2$. These two facts prove that $LiMn_2O_4$ battery has a higher thermal stability than $LiCoO_2$ battery.

(c) Durability

Poor durability is the main drawback of $LiMn_2O_4$ battery. Severe capacity loss is observed during cycling due to factors as follows:

1. Jahn-Teller effects. It refers to an inhomogeneity in discharge and a formation of tetragonal $Li_2Mn_2O_4$ compound. This causes the $LiMn_2O_4$ structure undergoes a lattice distortion on its surface[40].
2. Manganese tends to dissolve in electrolyte[41].
3. The two cubic phases will cause structure instability[42].
4. Degradation of crystallinity is observed[41].

It has shown that substituting metal cations for manganese in $LiMn_{2-y}M_yO_4$ (M=Li, Mg, Al, Cr, Co, and Ni)[43, 44] and surface modification with metal oxides[45, 46] are the two effective ways to improve its cycle performance.

i. Cation substitution for manganese

Experimental results in Figure 7[47] shows that untreated $LiMn_2O_4$ cathode suffers capacity loss of 41.67% after 50 cycles at C/5 discharge rate under room temperature. While the cation substituted counterpart ($LiMn_{1.9}Ni_{0.1}O_4$) loss is only 6.67%. Similar method has been used by LG Chemical Co., Ltd. with results shown in

Figure 8[48]. Although cation substitution is an effective approach for improving $LiMn_2O_4$ battery cycle performance, there is no clear explanation yet. One earlier study argued that metal cations can increase $LiMn_2O_4$ compound oxidation states above 3.58, consequently suppress Jahn-Teller distortion. However, investigation by Shin et al in 2003 suggests that manganese oxidation states for $LiMn_{1.9}Ni_{0.1}O_4$, $LiMn_{1.9}Co_{0.05}Li_{0.05}O_4$, and $LiMn_{1.85}Ti_{0.075}Li_{0.075}O_4$ are the same, but their capacity loss are different (4.3% to 20.7%). This observation indicates that capacity fading could be more complicated than the previous thought.

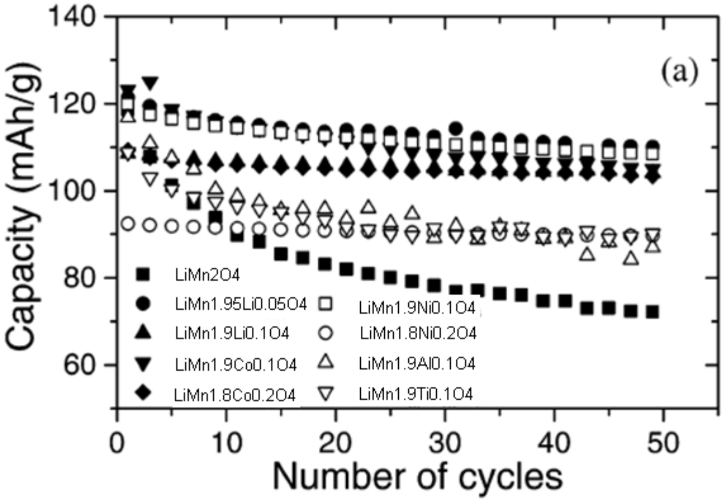


Figure 7 Cycle Performance of Metal Cations Substituted $LiMn_2O_4$ battery

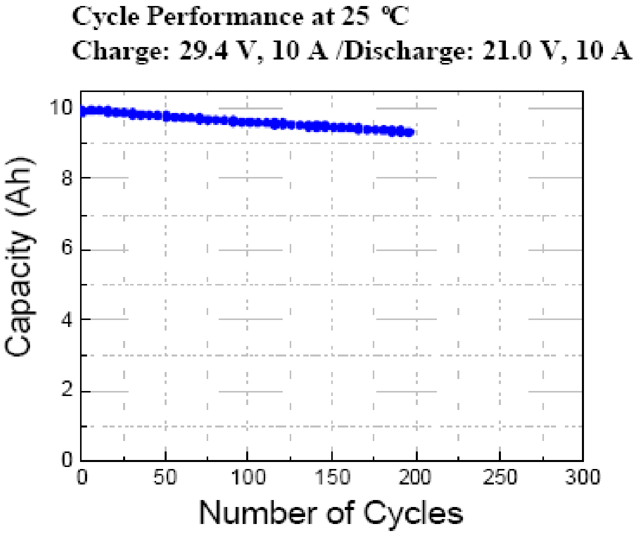


Figure 8 Cycle Performance of LG Chem $LiMn_2O_4$ Battery

ii. Surface modification by metal oxide

Another effective way to enhance the cycle performance is to coat $LiMn_2O_4$ cathode surface with $LiCoO_2$ and V_2O_5 proposed by Kannan et al[46]. The surface coating has effectively prevented the cathode particles from dissolving in acidic electrolyte. Experimental results in Figure 9 demonstrate that coated cathodes have more than 80% of capacity retention, while the uncoated one has only 55%.

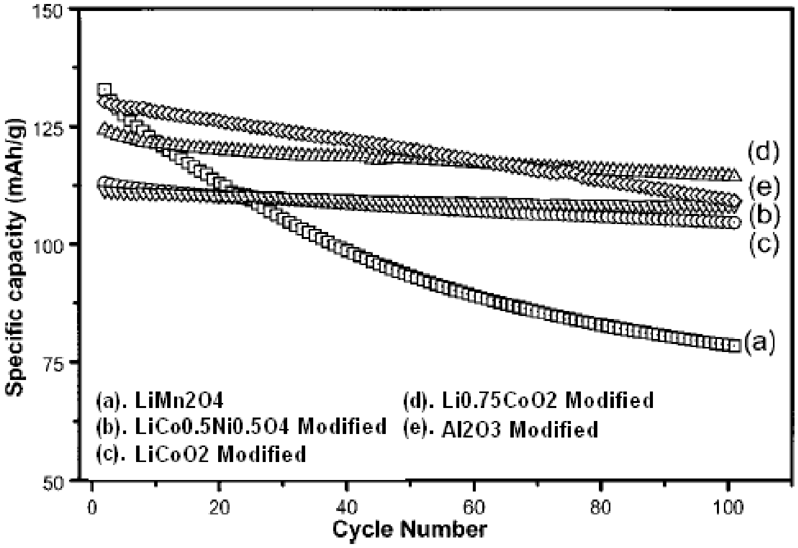


Figure 9 Cycle Performance of Surface Modified $LiMn_2O_4$ Battery

(d) Cathode synthesis

Synthesis for coated cathode is shown in the following steps described by US Patent 7056486[49]. The coating material is a mixture of lithium compound $LiOH \cdot H_2O$ and manganese compound $Mn(CH_3COO)_2$ in a mole ratio of Li to Mn 1:2. The compound is dissolved in anhydrous alcohol and stirred for more than 30 minutes. The coating element is mixed with $LiMn_2O_4$ in 7% mol fraction then heated at 480°C for 10 hours with dripping air at 0.1 liter/gh rate. The final compound has a formula of $Li_{1.03}Mn_{1.97}O_{4.02}$.

2.1.3 Lithium Iron Phosphate Battery

Lithium Iron Phosphate ($LiFePO_4$) battery was first invented by John Goodenough's group at University of Texas, Austin in 1996[50]. Unlike previous layered and spinel structures, it has a hexagonal stacking of oxide ions often referred to as olivine structure. The general formula is

M_2XO_4 with structure schematic shown in Figure 10. The two octahedral sites in olivine are crystallographically distinct with different sizes, thus $LiFePO_4$ compound has an ordered cation distribution[51]. In addition, the covalent bond existed in tetrahedral polyanion structure $(XO_4)^{n-}$ (X=P, S, As, Mo, or W) is believed to bring the redox potential to a higher energy level yielding a higher voltage and energy density[52, 53].

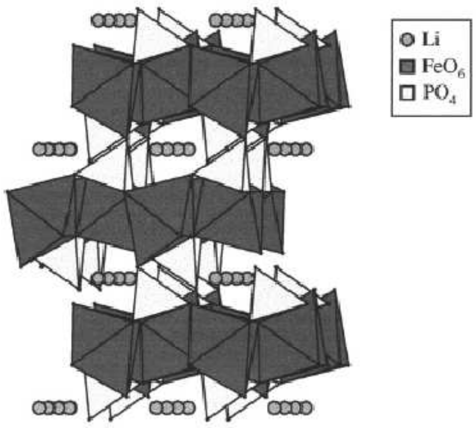


Figure 10 $LiFePO_4$ Structure

(a) Power and energy densities

$LiFePO_4$ battery is able to deliver a theoretical capacity as high as 170mAh/g with 3.5V intercalation voltage relative to lithium metal[13]. However, upon delithiation, $LiFePO_4$ compound will experience a 1st order phase transition to orthorhombic $FePO_4$ which indicates $Li_{1-x}FePO_4$ compositions actually have two phases $LiFePO_4$ and $FePO_4$. Both of these two phases are insulating due to Fe^{2+} and Fe^{3+} valency. Therefore, this intrinsic insulating property has limited its rate capability and energy density because of low electronic conductivity and slow diffusion of lithium ions across the two-phase boundary[13, 54]. Typically, electronic conductivity of an untreated $LiFePO_4$ cathode is 10^{-9}S/cm under room temperature[55], much lower than that of $LiCoO_2$ cathode 10^{-3}S/cm[56] and that of $LiMn_2O_4$ 10^{-5}S/cm[57]. Thus various methods have been proposed to increase its conductivity.

i. Carbon coating of $LiFePO_4$ particles

Carbon coating technique was first developed by Ravet et al in the year 2001[58]. By coating the particle surface with 1%wt of carbon, 160mAh/g capacity can be obtained at 1C rate. Further study was conducted by Huang et al[54], in which carbon coated $LiFePO_4$ particles in nanosize are prepared by mixing raw materials with carbon gels. The result has shown that 100nm-200nm coated $LiFePO_4$ particles can enhance capability of extracting Li ions from olivine structure shown in Figure 11. After charging process, 98% of Li ions are extracted, and 95% of Li ions are recovered in the reverse way. 110mAh/g capacity can still be obtained at 5C discharge rate. Furthermore, above 90% of initial capacity is maintained at 5C and C/5 discharge rate.

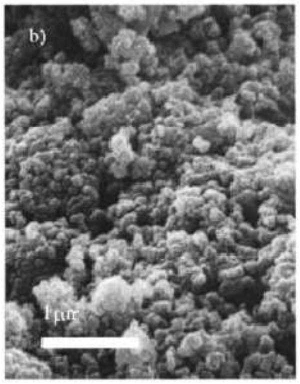


Figure 11 Carbon Coated $LiFePO_4$ Particles

ii. Metal doping of $LiFePO_4$ particles

Metal doping in $LiFePO_4$ particles was first carried out by professor Chiang's group in MIT in the year 2002[13]. By using metal cations doping, conductivity of $LiFePO_4$ is increased above 10^{-2}S/cm, 10^8 times higher than the undoped counterpart. Doping metal cations in lithium deficient stoichiometry ($Li_{1-x}M_xFePO_4$) shows no impurity phase after synthesis. On the other hand, both untreated $LiFePO_4$ particles and metal doped in iron deficient stoichiometry $LiFePO_4$ particles show impurity phases. Presence of impurity phase will increase the impedance of cathode thus decrease its conductivity. The results have proven that battery is able to discharge at 40C rate (6000mA/g).

By applying the same topology, power and energy densities for cathode and battery are estimated based on the discharge curve obtained from Chung et al[13]. The results are shown in Table 5 and Table 6 (calculation details are shown in Appendix A).

Discharge C-rate	Current (mA/g)	Voltage (V)	Capacity (mAh/g)	Power density (W/kg)	Energy density (Wh/kg)
C/10	15	3.5	150	52.5	525
C/2	75	3.5	130	227.5	455
1C	150	3.5	120	414	414
2C	300	3.4	110	748	374
4C	600	3.3	100	1320	330
10C	1500	3.25	85	2762	276
20C	3000	3.2	65	4160	208

Table 5 Doped $LiFePO_4$ Cathode Power and Energy Densities

Discharge C-rate	Power density (W/kg)	Energy density (Wh/kg)
C/10	15.75	157.5
C/2	68.25	136.5
1C	124.2	124.2
2C	224.4	112.2
4C	396	99
10C	828	82.8
20C	1248	62.4

Table 6 Doped $LiFePO_4$ Battery Power and Energy Densities

(b) Safety

$LiFePO_4$ is an intrinsic safe cathode. When it is exposed to extreme conditions such as overcharging and overheating, the strong covalent bond between oxygen and P^{5+} which forms $(PO_4)^{3-}$ units will ensure a much higher thermal stability than the weak polar oxygen–metal bond. No oxide breakdown is observed until 800℃. The strong covalent bonding also stabilizes the anti-bonding Fe^{2+}/Fe^{3+} state through a Fe-O-P inductive effect. As a result, oxygen is difficult to be extracted during cathode decomposition at high temperature[59].

(c) Durability

The olivine structure is inherently stable during cycling. In the study of $LiFePO_4$ cathode cycle performance by Imachi et al[34] from Sanyo Electric Company, it was found that at charging voltage above 4.2V, most of the lithium ions are extracted from $LiFePO_4$ cathode. On the other hand, only half of the lithium ions can be extracted from $LiCoO_2$ cathode. The excess lithium will plate onto the anode. This will degrade capacity reversibility, and safety. In the experiment by A123 system, they have demonstrated that the $LiFePO_4$ battery is able to retain 95% of its initial capacity after 1000 cycles discharge at 1C rate under 25℃ with 100% Depth of Discharge (DoD)[60].

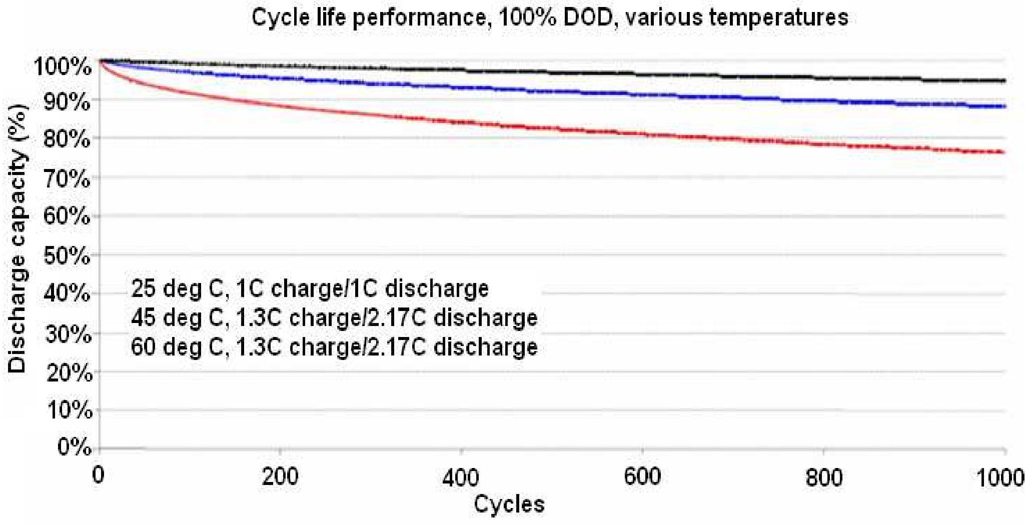


Figure 12 Cycle Performance of A123System $LiFePO_4$ Battery

(d) Cathode synthesis

According to US Patent 7338734[61], large scale production of doped $LiFePO_4$ nanoparticles can be achieved by solid-state reaction method. Starting materials for 1mol % Nb-doped $LiFePO_4$ (4g batch) are shown in Table 7.

Compound	Manufacturer/Purity (wt%)	Weight (g)
Li_2CoO_3	Alfa-Acsar, 99.999	0.7316g
$FeC_2O_4·2H_2O$	Aldrich, 99.99	3.7867g
$NH_4H_2PO_4$	Alfa-Aesar, 99.998	2.3006g
$Nb(C_6H_5O)_5$	Alfar-Aesar	0.1116g

Table 7 Starting Materials for Doped $LiFePO_4$ Battery

Materials are ball milled in a polypropylene jar for 20 hours in acetone. Afterwards, the mixture is dried under temperature less than 100°C, then ground with a mortar and pestle in an argon box. The first heat treatment at 350°C for 10 hours in a flowing N_2 or Ar atmosphere is carried out followed by grounding with mortar and pestle. Consequently, the second heat treatment is carried out at 600°C-850°C for 15-24 hours in a flowing N_2 or Ar atmosphere. The final product with formula $Li_{0.99}Nb_{0.01}FePO_4$ is obtained.

2.1.4 Lithium Nickel Cobalt Manganese Oxide Battery

The composite oxide cathode which consists three transition metals was first proposed by Liu et al[62] in 1999. Among them, layered structure of lithium nickel cobalt manganese oxide ($Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$) cathode was developed intending to offer a safer battery with better cycling performance. Each element in the composite oxide plays a significant role. Ni is the electrochemically active specie; Mn provides stability to the structure during cycling, and cobalt helps order the Li and Ni ions[63]. Further studies have been carried out by various research groups such as Ohzuku et al[64], and Thackeray et al[65] in recent years.

(a) Power and energy densities

The cathode delivers high capacity (more than 200mAh/g when cut-off voltage is 4.6V), and high rate capability[66]. This is because lithium ions are able to diffuse through the two dimensional interlayer space at presence of Co and Ni ions and it results in a high current. In addition, with presence of Mn^{4+}, $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathode is able to obtain a stable thermal states during cycling[67]. Abraham et al[68]discovered that unfavorable oxidation of Ni to tetravalent state is greatly suppressed due to small amount of Ni present in the cathode. With reduced impedance growth, structure stability is enhanced. In spite of higher capacity compared to other Li-ion batteries, its rate capability is not significantly improved. This is due to its low tap density. Various studies have been carried out to further increase its power density for $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathode as described below.

i. Metal substitution for cobalt in $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$

Wilcox et al[67] have investigated effects of various metal substitutions in 2009. The result shows that iron substituted cathode ($LiNi_{1/3}Co_{1/4}Fe_{1/12}Mn_{1/3}O_2$) gives a lower capacity and poorer rate capability than the untreated one when cycled between 4.3V and 2V. The reason is antisite cation defect concentration has impeded lithium ions transportation. For Al substituted cathode ($LiNi_{1/3}Co_{1/3-y}Al_yMn_{1/3}O_2$ ($0 \leq y \leq 1/4$)), although there is a drop in capacity at start of cycling, capacity retention and rate capability are enhanced after 5 cycles due to a decrease in antisite and increase in lithium slab dimension. Ti substituted cathode ($LiNi_{1/3}Co_{1/4}Ti_{1/12}Mn_{1/3}O_2$) gives the highest capacity and best cycle performance as illustrated in Figure 13. By replacing Co^{3+} with Ti^{4+} ions, lithium ions diffusion through adjacent tetrahedral vacancy is enhanced. By applying the same topology, power and energy densities for cathode and battery are estimated based on the experimental data obtained from Yabuuchi et al[66]. The results are shown in Table 8 and Table 9(calculation details are shown in Appendix A).

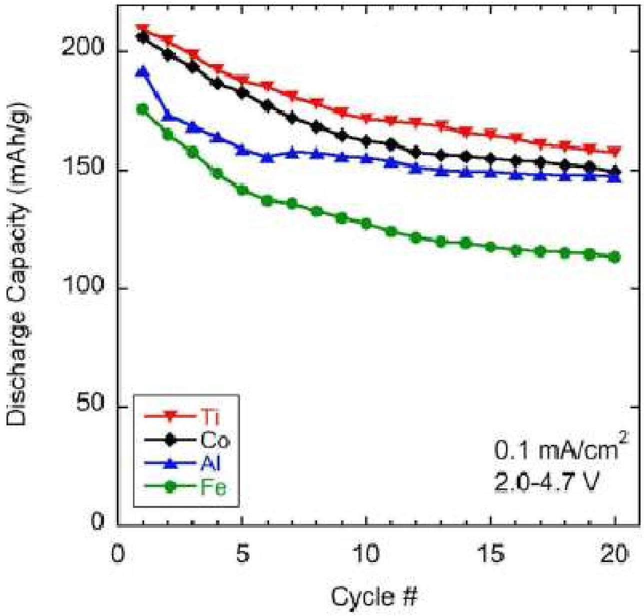


Figure 13 Cycle Performance of Metal Substituted Li($Ni_{1/3}Co_{1/3}Mn_{1/3}$)O_2 Battery

Discharge C-rate	Current (mA/g)	Voltage (V)	Capacity (mAh/g)	Power density (W/kg)	Energy density (Wh/kg)
C/10	18.3	4.25	200	85	850
C/4	50	4.25	190	202	808
C/2	100	4.1	175	359	718
C	200	4	170	680	680
2C	400	4	160	1280	640
4C	800	3.8	150	2280	570

Table 8 Li($Ni_{1/3}Co_{1/3}Mn_{1/3}$)O_2 Cathode Power and Energy Densities

Discharge C-rate	Power density (W/kg)	Energy density (Wh/kg)
C/10	25.5	255
C/4	60.6	242.4
C/2	107.7	215.4
C	204	204
2C	384	192
4C	684	171

Table 9 Li($Ni_{1/3}Co_{1/3}Mn_{1/3}$)O_2 Battery Power and Energy Densities

(b) Safety

With less cobalt, $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathode has a better thermal stability than $LiCoO_2$ cathode. Yoshizawa et al[69] have shown that the cathode will only experience exothermic reaction at 265℃ with 910J/g heat generated which is much lower than that of $LiCoO_2$. Although MnO_2 is stable at room temperature, neither NiO_2 nor CoO_2 is, both have oxygen partial pressure of more than 1 atm during operation[70]. In addition, its exothermic reaction behavior is more rapid compared with $LiCoO_2$ battery which means the battery will immediately ruptures and ignites once thermal runaway takes place[71]. Hence, the safety is still an issue for this battery.

(c) Durability

As shown before, its cycling performance at voltage ranges from 2.0V to 4.3V was investigated at C/20 discharge rate. A capacity loss of 3% is observed after 20 cycles. When the voltage operates between 2V and 4.7V, the cell is able to achieve initial capacity as high as 200mAh/g, but the capacity loss increases to 25% after only 20 cycles of operation[67]. This degradation is caused by reduction of manganese ions on the graphite surface which resulted in a significant increase of the charge transfer impedance at anode and electrolyte interface. In order to improve the durability, alternative electrolyte lithium bisoxalatoborate, $LiB(C_2O_4)_2$ (“LiBoB”) is proposed by K. Amine et al[72]. This electrolyte does not produce acidic element which causes Mn^{2+} dissolution. The result in Figure 14 shows 5% capacity loss after 100 cycles.

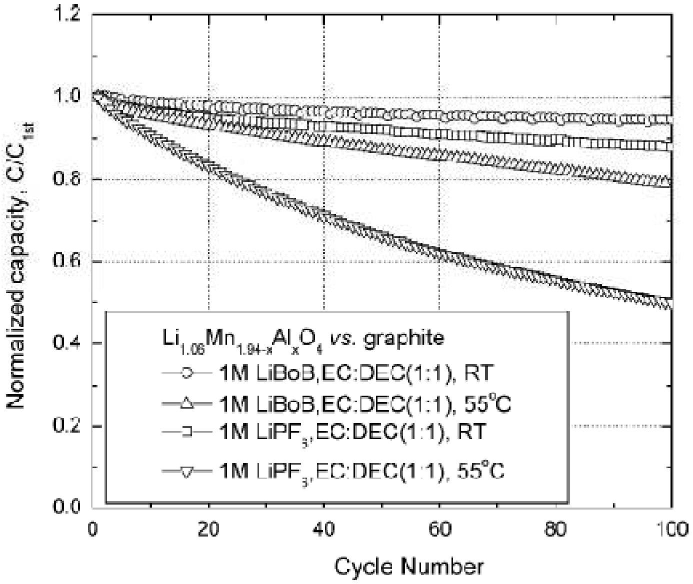


Figure 14 Cycle Performance of $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ Battery with $LiB(C_2O_4)_2$ electrolyte

(d) Cathode synthesis

According to US Patent 2007/0292763[73], $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathode can be synthesized in the following steps: first carbonate co-precipitation method is used to prepare $Ni_{1/3}Co_{1/3}Mn_{1/3}CO_3$ where solution of $NiSO_4$, $CoSO_4$, and $MnSO_4$ with Ni:Co:Mn=1:1:1 and concentration of 2 mol/dm^3 is stirred under CO_2 atmosphere at 50°C for 12 hours. Parameters such as PH=7.5, temperature, and stirring speed=1000rpm must be controlled carefully to form $Ni_{1/3}Co_{1/3}Mn_{1/3}CO_3$. Then the compound is dried and decomposed at 600°C for 5 hours to obtain $Ni_{1/3}Co_{1/3}Mn_{1/3}O_{2+y}$. The intermediate composite will be mixed with Li_2CO_3 and MoO_3, and the mixture will be heated to 900°C at rate of 100°C/hour. Lastly by maintaining the mixture for 20 hours, the $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})Mo_xO_2$ is obtained.

Chapter 3 Market Analysis

3.1 Market Analysis of Lithium Ion Battery

3.1.1 Market Demand

As mentioned in chapter 1, Li-ion batteries are ahead of lead acid (PbA) battery, NiMH battery, and ultracapacitor in terms of low cost, and high power and energy density in combination. Thus, in the past 8 years, the global sales volume has increased by 376%. In 2008, 2.71 billion units of Li-ion batteries were sold across the world with a sales value of $8.03 billion as shown in Figure 15 and Figure 16. The major demand of Li-ion battery came from the mobile phone market which accounts for 60% of total consumption[74]. Demand from other cordless devices such as power tools, lawn/garden tools, portable medical devices, and handheld tracking device etc is also increasing. Small lithium ion batteries have proven the feasibility of this technology, large emerging markets are for hybrid and battery electric vehicles powered by the renewable energy systems[75].

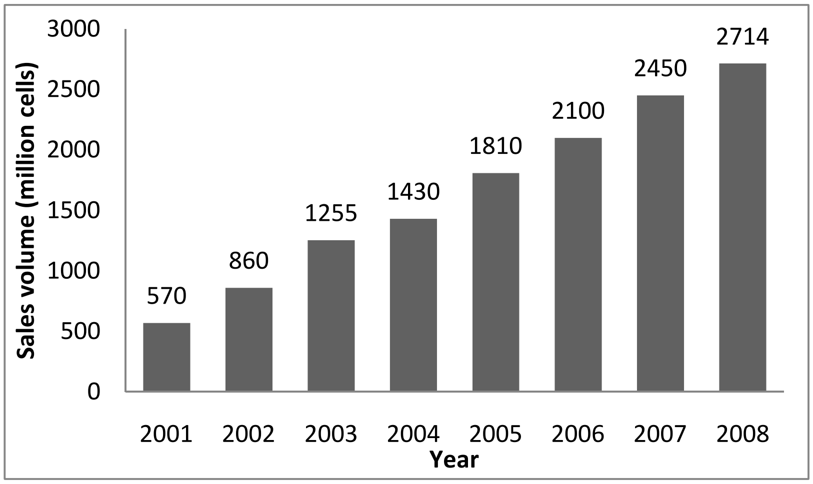


Figure 15 Li-ion Battery Global Sales Volume

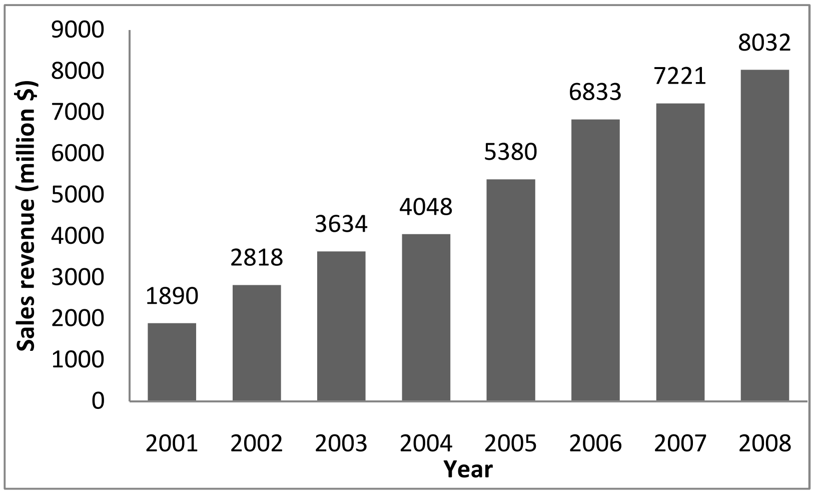


Figure 16 Li-ion Battery Global Sales Revenue

For the automotive industry, currently, most of the HEV are using NiMH batteries as energy storage system as shown in Figure 17. With increasing number of HEV shown later, the market of NiMH battery has also increased to $900 million in 2008 compared with $600 million in 2006[76]. Toyota Panasonic EV Energy (PEVE) is the main supplier for automotive NiMH battery[19]. Due to the fact that NiMH battery has a low energy density, size and cost of its battery pack will create a big problem if it is implemented in PHEV and BEV which require high energy for their electric drive. In addition, it is highly unlikely for NiMH battery to achieve cost reduction since Ni is a relatively expensive metal. Thus efforts have been put into developing a more reliable and cost-effective Li-ion battery. It is worth to note that global investment in Li-ion battery R&D will continue to increase with $1 billion per year which is several times the total investment in other batteries R&D[19]. With continuous improvement, Li-ion battery is expected to dominate the battery market in near future shown in Figure 18. And Figure 19 shows that the number of Li-ion battery will reach 11.88 million in 2020 2.57 times the number in 2015. The demand in HEV at year 2020 is 8.8million 74.3% of total demand. Hence, there is a huge potential for Li-ion battery market.

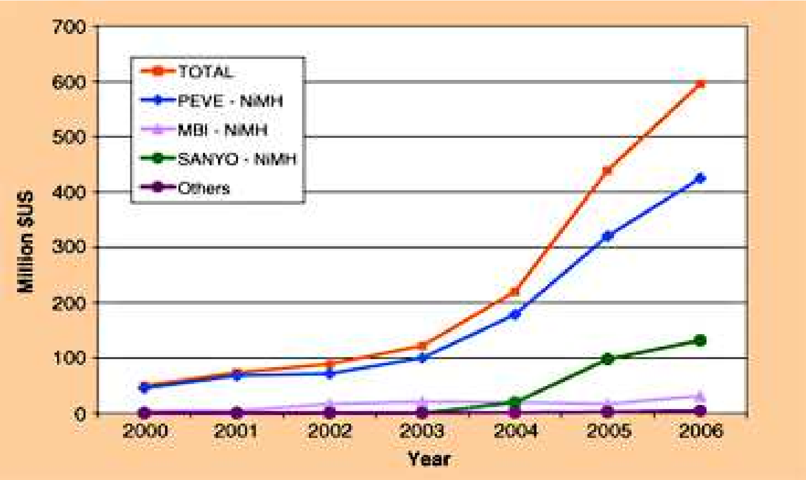


Figure 17 HEV Battery Market

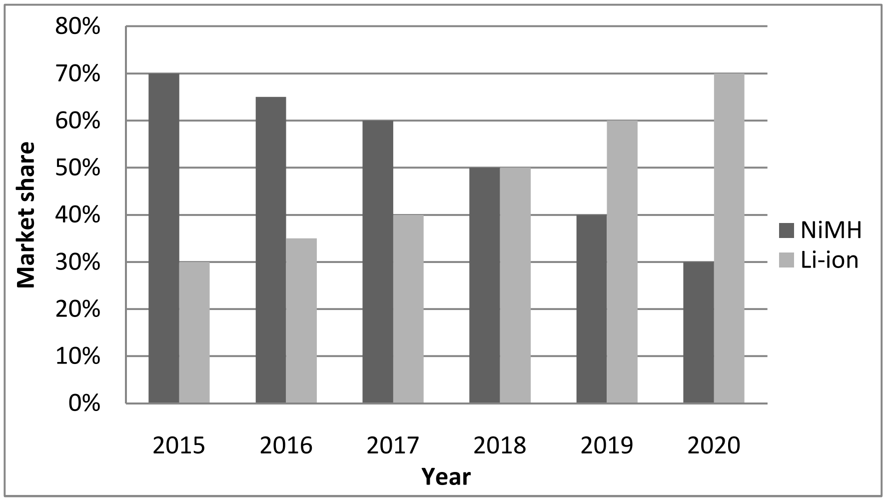


Figure 18 Global Market Share of HEV Batteries

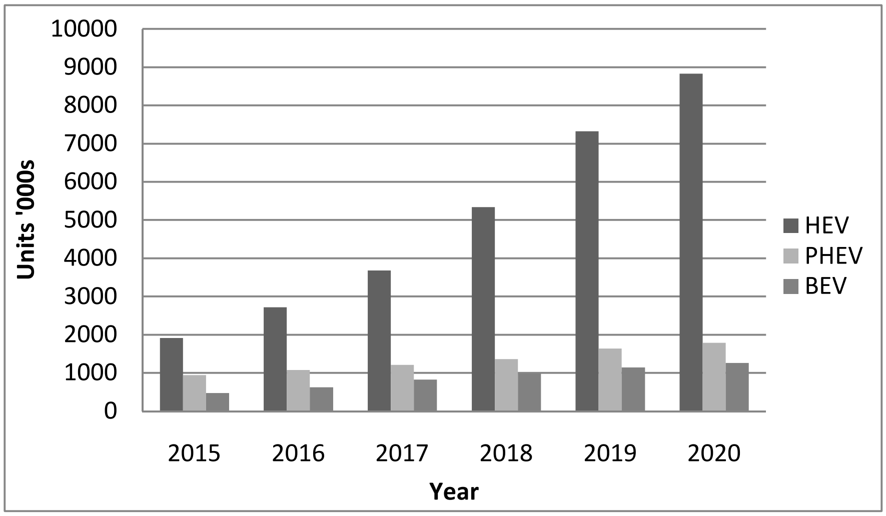


Figure 19 Global Li-ion Battery Demand Projection

3.1.2 Lithium Ion Battery Key Suppliers

Li-ion battery companies shown in Table 10[18] are being considered by global automotive manufacturers as key developers for energy storage system used in future electric vehicles. Diversifications in Li-ion batteries have led to intense competitive rivalry among all the companies.

Cathode	Anode	Electrolyte	Company
LMO	Graphite	Gel	LG Chem
LMO	LTO	Liquid	EnerDel
LMO/NCM	Blend	Liquid	Sanyo
LMO/NCM	Graphite	Liquid	Samsung
LMO/NCM	Hard carbon	Liquid	Hitachi Vehicle Energy
LMO/NCA	Hard carbon	Liquid	GS Yuasa
LFP	Graphite	Liquid	A123 System
LFP	Unkonwn	Liquid	BYD
LFP	Unknown	Polymer	Valence
NCM	Graphite	Liquid	Imara (Lion Cells)

Table 10 Key Li-ion Battery Suppliers

Sanyo Electric Co Ltd

Sanyo Electric currently produces NiMH battery for Honda and Ford HEV. It has announced its investment plan to further produce Li-ion batteries for HEV and PHEV. Recently, it has signed a partnership with Volkswagen to develop Li-ion batteries for HEV[19].

Samsung SDI

Samsung SDI is the third leading Li-ion battery manufacturer behind Sony and Sanyo. Its main business is focusing on developing Li-ion batteries for consumer electronics and power tools. It has not signed any contract to produce Li-ion battery for automotive application yet[19].

A123 System

A123 System is a US based company founded in 2001. It is commercializing advanced

$LiFePO_4$ battery using nanotechnology process. It is working on 8 development contracts and 5 production contracts for world major automotive producers. Other contracts include batteries for aircraft, power tools, and electric utilities[19]. Recently, it has secured more than $100 million in refundable tax credits from the state of Michigan and has selected Livonia as one of the sites where it is planning to base new production plants[77].

LG Chem

LG Chem is mainly produces Li-ion batteries for portable devices. Its subsidiary company Compact Power Inc (CPI) is a member of USABC which focuses on developing lithium ion batteries for automotive application using $LiMn_2O_4$ based cathode. Hyundai Electra has already signed a contract with CPI to develop the battery for its upcoming electric vehicles[78]. The company has been selected by GM for Li-ion battery production used in Chevy Volt during Jan. 2009[79].

EnerDel

EnerDel was formed as a partnership between Ener1 and Delphi in 2004. It is now producing Li-ion batteries for HEV manufacturers. Furthermore, EnerDel has signed one contract with Think City recently to develop batteries for electric vehicles[80]. $LiMn_2O_4$ cathode with $Li_4Ti_5O_{12}$ anode is used in its battery which claims to have improved cycle life.

Hitachi Vehicle Energy Ltd

Hitachi Vehicle Energy is a joint venture between Hitachi (NYSE: HIT; TSE: 6501) (65%) and Shin-Kobe Machinery (TSE: 6934) (25%), and Hitachi Maxell Ltd (TSE: 6810) (10%). HVE uses $LiMn_2O_4$ based cathode in its automotive batteries. Hitachi was appointed as Li-ion supplier for GM mild HEV[19].

BYD

BYD is a China based company founded in 1995. It is initially delivering nickel-cadmium batteries and Li-ion batteries for cell phones. In the year 2003, it enters automotive industry and it has achieved the whole-car manufacturing from $LiFePO_4$ battery to vehicle[81]. Recently, the Chinese carmaker has formed a partnership with Volkswagen to explore the hybrids and electric vehicles powered by lithium batteries[82].

Valence

Valence was founded in 1989 with headquarter in Austin, Texas. It produces $LiFePO_4$ battery for automobile, electric system, and military applications. Tanfield Group has signed a contract with Valence to produce electric trucks and vans for both European and US markets[83].

Imara

Formerly known as Lion Cells, Imara was founded in 2006 with headquarter in Menlo Park, California. Its core technology nickel cobalt manganese based Li-ion battery is licensed from Stanford Research Institute (SRI) targeting at high power applications such as electric tools and electric vehicles. On December 15th, 2008, it officially launched its plan to deliver U.S.-based energy storage solutions[84].

3.1.3 Commodity Market

Raw material is the key player in Li-ion battery manufacture, and it determines the battery cost. Besides lithium which is the primary metal used in the battery, other metals such as cobalt, nickel, copper, iron, manganese, and phosphate etc will have a significant rise in their demands due to increasing numbers of Li-ion batteries as shown in Figure 20[19]. However, most of these metals are in structural deficits throughout current commodity cycle. As a result, new production sites are being explored to reduce supply and cost risks.

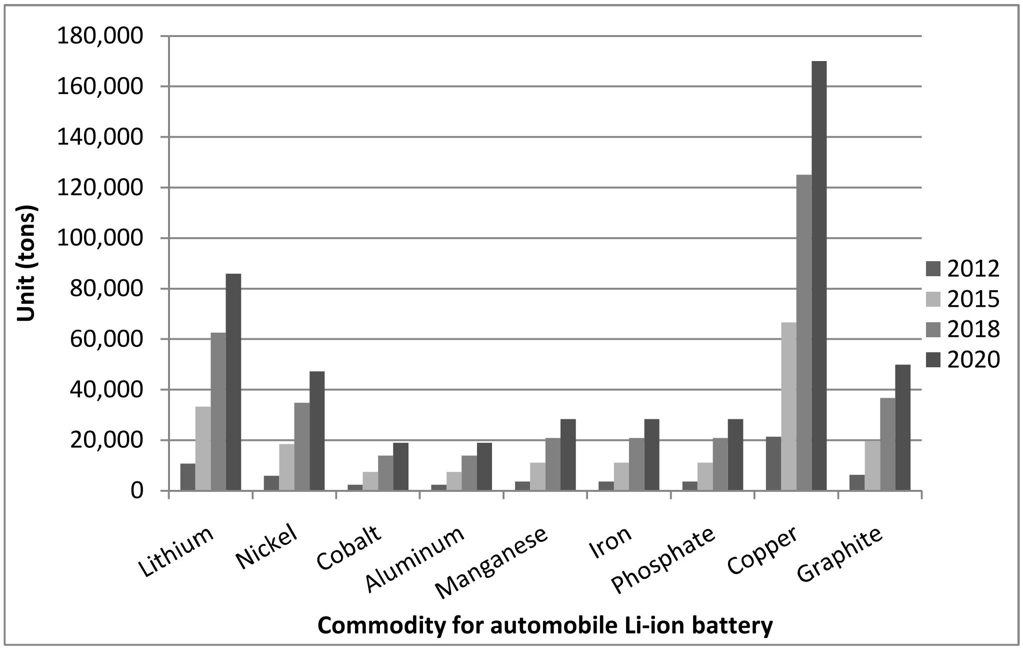


Figure 20 Commodity Demand in Li-ion Battery for Automotive Industry

Lithium

The primary use of lithium is in Li-ion batteries for consumer electronics and power tools. Other uses include lubricating greases and ceramics. Lithium carbonate Li_2CO_3 is the direct input for lithium in the battery manufacturing. Majority of this raw material is produced from Chile (55%), China (17%), Argentina (16%), and other countries such as United States (12%). Fast growing consumer electronics industry has boosted lithium production by 38% from 2003 to 2007. Further demand from automotive industry is foreseen by countries like China to expand its lithium production which will add significant amount to the global production in near future. With lithium demand growing at 7% per year, it is predicted that production of lithium at end of year 2010 will be as twice as that in 2006 shown in Figure 21[19]. Factors like additional lithium mining sites, new technologies which uncovers lithium from other resources, and large-scale of battery recycling, will enable the supply to meet the demand for automotive battery applications in the long term[19].

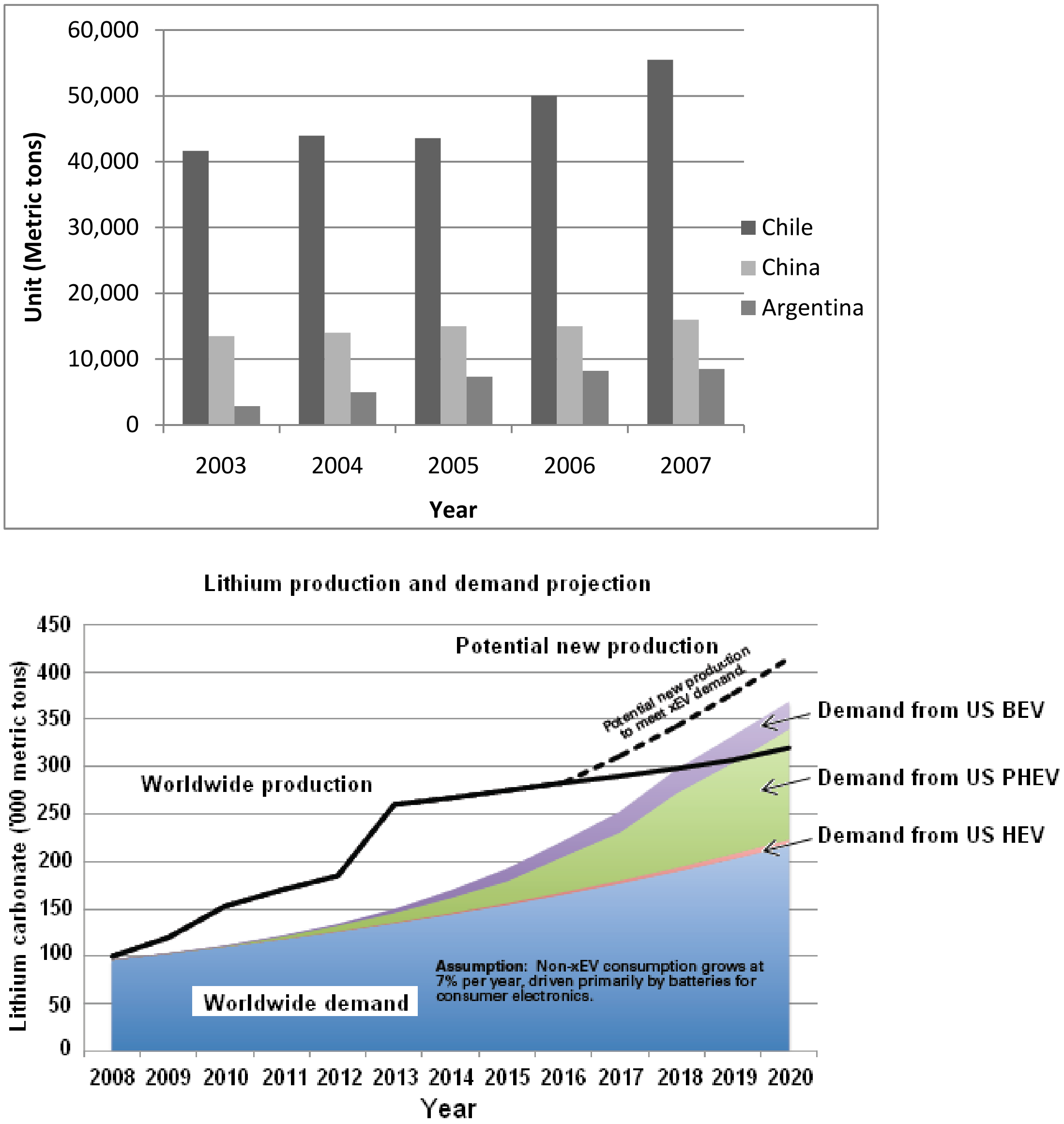


Figure 21 Key Lithium Production Countries and Lithium Market Outlook

Cobalt

Cobalt is extensively in superalloys for automotive, aerospace, and audio applications. With increasing demand for Li-ion batteries, cobalt demand has shown a significant increase in recent years. Producers from Central Africa and China have planned to expand their productions to meet the demand in the long term[85]. Even with production expansion, the price of cobalt is unlikely to drop significantly in near future unless new production sites are discovered potentially in the countries like The Democratic Republic of Congo and Zambia. Cobalt historic production volume and price are summarized in Table 11.

	2005	2006	2007	2008E	2009E	2010E
Production (tonnes)	54,910	54,710	58,384	64,719	68,914	73,985
Consumption (tonnes)	54,044	57,023	60,838	64,977	69,114	73,585
Price (USD/kg)	31.96	33.73	61.5	99.428	66.14	55.12

Table 11 Global Cobalt Market Statistics

Nickel

The biggest market for nickel is in stainless steel sector which is also an input to the automotive and aerospace industry. The demand for nickel follows a gradual increase in the past 4 years shown in Table 12[19], and its supply and price in future still remains a risk as number of large-scale producers is limited.

	2005	2006	2007	2008E	2009E	2010E
Production(thousand tonnes)	1288	1361	1463	1542	1674	1809
Consumption (thousand tonnes)	1264	1376	1429	1570	1659	1787
Price (USD/t)	14,751	24,237	37,060	29,652	27,889	24,471

Table 12 Global Nickel Market Statistics

Copper

Copper is mainly used in power, telecommunications infrastructure, and commercial constructions. Demand for copper was overwhelming during last decades, and it will continue to grow as shown in Table 13 due to high demand from developing world.

	2005	2006	2007	2008	2009	2010
Production (million tonnes)	16.54	17.32	18.13	19.02	20.22	21.11
Consumption (million tonnes)	16.98	17.53	18.23	19.09	20.01	20.77
Price (USD/t)	3682	6725	7091	7519	6917	5512

Table 13 Global Copper Market Statistics

3.2 Market Analysis for Electric Vehicles

Figure 22 demonstrates the global markets for advanced batteries. Among them, the advanced portable market has the largest share of the market. Valued at $3.4 billion in 2007, this segment is expected to be worth $4.2 billion by 2012, an annual growth rate (AGR) of 4.1%. The second largest segment, advanced stationary, was worth an estimated $3 billion in 2007 and will reach $3.7 billion by 2012. The largest increase in this segment will be for uninterruptible power supply (UPS) and smaller remote stationary applications to protect data during power outages. For instance, the global UPS battery market is expected to grow from $2.5 billion in 2007 to over $3 billion by 2012. Motive applications include the largely mature markets for traction, marine and aviation batteries; it is currently a $1.6 billion segment that will be worth $1.7 billion in 2012 with AGR of 1.3%. The $789 million electric vehicle segment will reach $1.5 billion by 2012 with AGR of 14.3%. In near future, there is a big potential market for Li-ion batteries in automotive industry[86].

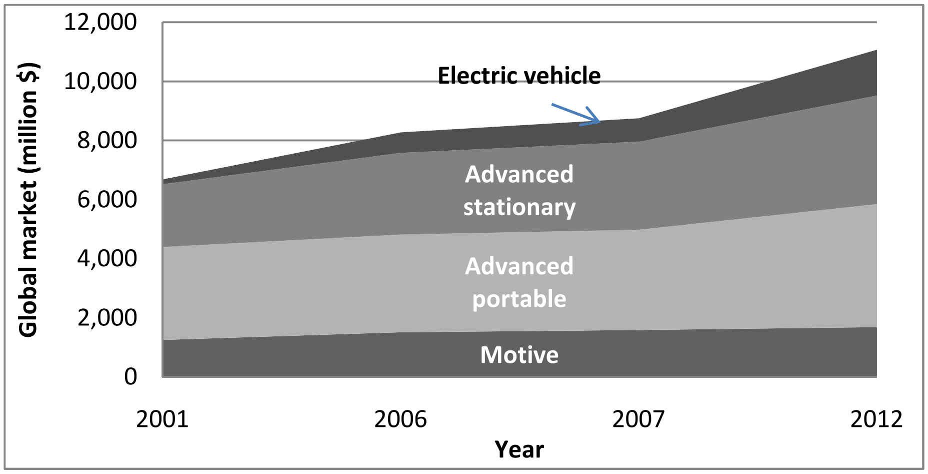


Figure 22 Global Markets for Advanced Batteries

3.2.1 Electric Vehicle Overview

HEV

HEV uses gasoline as primary energy source to power up its internal combustion engine (ICE) and electric motor. This vehicle operates in charge sustaining (CS) mode which means the battery is running about half-way between fully charged and fully discharged states[8], the battery can provide a power assist to the vehicle by capturing kinetic energy from deceleration and braking,. In addition, idling gasoline consumption is reduced by shutting down the ICE. As a result, HEV is more fuel efficient than gasoline car[87]. Recently, attention has been focused on developing more gasoline independent vehicles such as PHEV and BEV.

PHEV

PHEV is a plug-in hybrid electric vehicle with high energy storage battery that can be recharged by plugging to an electric power grid. Typically, PHEV has dual operation modes: Charge Depletion (CD) mode which means PHEV operates solely on electricity to power up the vehicle and Charge Sustaining (CS) mode similar to HEV. PHEV will initially operate in CD mode until the battery power is too low to support the vehicle, then it switches to CS mode[76]. Based on its design, PHEV can be further categorized into two types. The first type requires battery with high energy density to ensure a long electric-driving range; while the second type requires battery with high power density to be capable of delivering power assist to the vehicle[76].

BEV

Unlike HEV and PHEV, battery electric vehicle (BEV) does not have any combustion engine. It is operating solely in CD mode in which electric motor and controller will convert the electricity stored in the battery to power up the vehicle. To recharge BEV, the battery pack needs to be connected to the electric grid.

3.2.2 Electric Vehicle Market Growth

Many countries have been placing taxes, fees, and other regulations on ICE vehicles in order to reduce CO_2 emission. Meanwhile some countries are providing rebates to electric vehicles since electric vehicles offer both economical and environmental values.

French government has announced a “feebate” system which gives 5000 Euros to low CO_2 emission electric vehicles, and charge 200-750 Euros for ICE vehicles[88]. Denmark and Israel are offering free purchase tax for electric vehicles, while charging 60-150% of vehicle open market values (OMV) for ICE vehicles. California has set up the Zero Emission Vehicle program to regulate its CO_2 emission. Cities like Shanghai and Beijing have restricted numbers of gasoline cars by charging license fees 2-20% of vehicle OMV[19]. Besides government policies, electric vehicles are offering economic benefits to consumers as well. A mid-size strong hybrid sedan provides a 30% fuel-economy improvement over a gasoline counterpart. This will save 156 gallons of fuel for a driver whose annual mileage is 14,000 miles[76].

With above incentives, the number of HEV has increased from 24,000 to 384,000 globally in the past 6 years displayed in Figure 23[76]. This number is expected to grow further in next 15 years. Figure 25[19] shows that the number of HEV, PHEV, and BEV will reach 11,897,000, 1,433,000, and 1,009,000 by end of year 2020. That is 90.5% increase in PHEV and 167.6% increase in BEV markets from 2015 to 2020.

Increasing demand for electric vehicles has driven a competitive market among car manufacturers. Currently, 78.7% of HEV global market is dominated by Toyota, and the rest is shared by Honda(10.3%), Ford(7.3%), Nissan(2.3%), and GM(1.4%) as shown in Figure 24[18]. GM has already launched its PHEV Chevy Volt to be produced by end of November in 2010.

This PHEV will use manganese oxide based Li-ion battery for its electric power. With full charged battery, the PHEV is able to run 40 miles solely on electricity provided by its manganese oxide battery. In addition, the small gasoline tank is able to extend its range as far as 640 miles. The price of the PHEV has not been determined yet, but it is predicted that the battery pack will cost about $10,000 to $15,000 with 16kWh total energy which is equivalent to $625/kWh to $937.5/kWh. A list of electric vehicle models which will be launched in near future are shown in Appendix B[89].

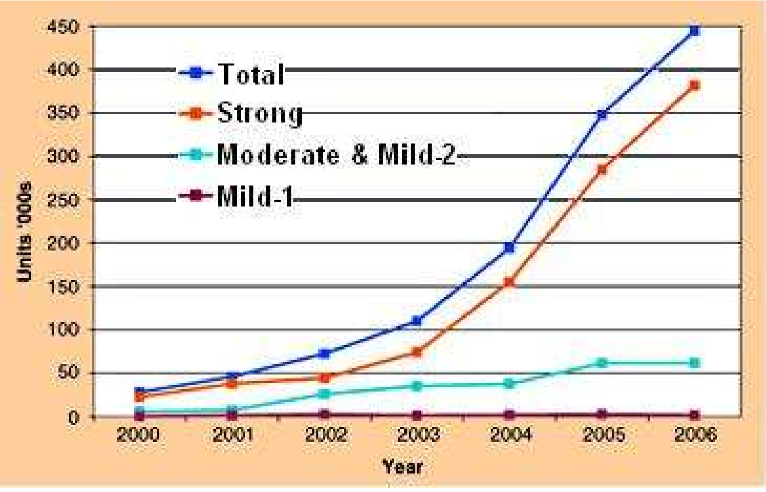


Figure 23 Global HEV Numbers

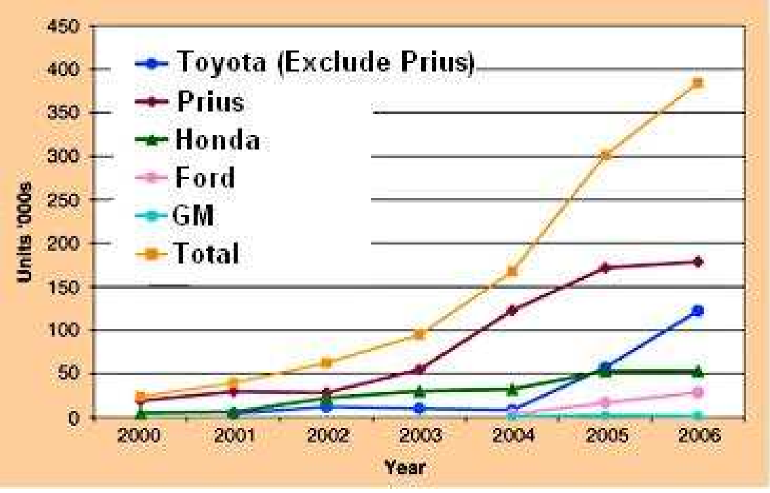


Figure 24 Global HEV Manufacturers

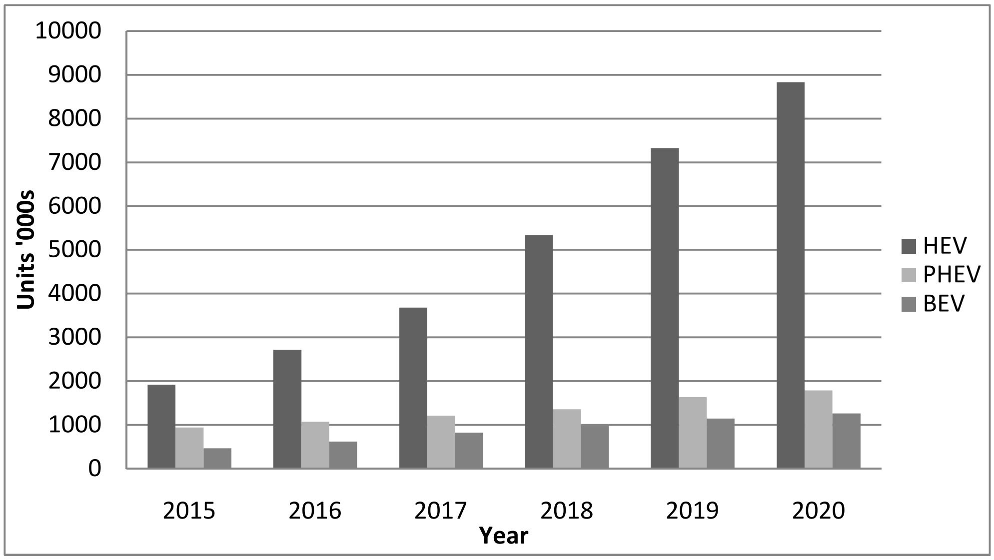


Figure 25 US and Europe Electric Vehicles Projection

Chapter 4 Technology Implementation

4.1 Intellectual Property

Intellectual property (IP) such as patents is critical for commercialization of new technologies. It provides information for the status of technology, and protects the company from its competitors. For example, Harwell, an English company, once controlled the $LiCoO_2$ battery IP until it expired in 2002. Every Li-ion battery company had to take a license on the patent. This has brought a large amount of profits to Harwell. Thus for a start-up company to sustain the competitiveness, having a unique IP is the key. Figure 26 shows the US patents hold by key Li-ion battery companies. Samsung SDI and Sanyo Electric are the two leading companies in terms of patent numbers. Their patents range from electrode design to electrolyte invention. Meanwhile they are targeting various markets mainly in portable devices such as mobile phones, notebook PCs, and power tools. On the other hand, companies such as Hitachi Vehicle Energy, EnerDel, A123Systems, and Compact Power Inc are mainly producing Li-ion batteries for automotive applications[19].

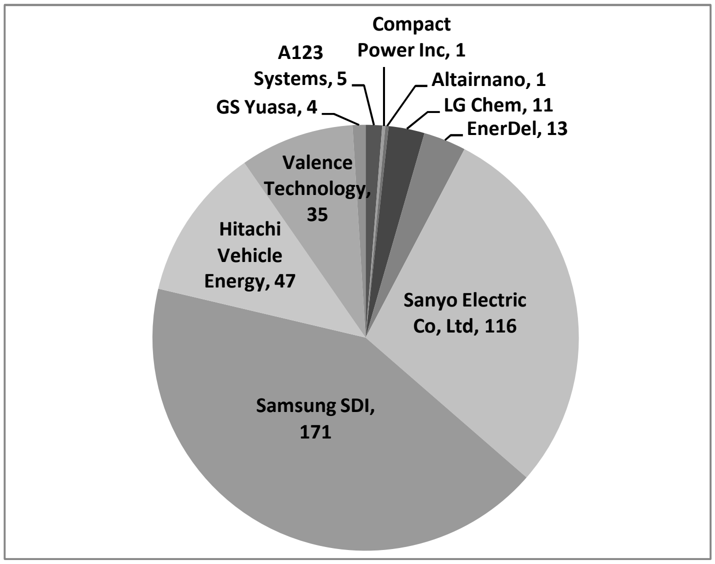


Figure 26 Li-ion Battery Patent Distributions by Company

Since cathode is a critical component mainly determining the battery performance, following sections will focus on discussion of key cathode patents.

4.1.1 $LiCoO_2$ Cathode Patents

In US Patent 6395426[90], it claims that surface of $LiCoO_2$ particle is attached with a substance from titanium, titanium oxide, and lithium titanium complex oxide. The mole ratio of $LiCoO_2$ to the substance is within the range of 1:0.00001 to 1:0.02. A non-aqueous electrolyte contains $LiN(SO_2C_2F_5)_2$. As a result, the battery's low temperature discharge is improved with better safety due to less internal gas generation.

Single layer coating is proposed in US Patent 6916580[36]. The cathode particle of a lithiated compound such as $LiCoO_2$ is coated with a layer of element where the coating layer have at least two coating elements with general formula of $M_pM'_qO_r$, where $0<p<1$, $0<q<1$, and $1<r\leq2$. M and M' are not the same and each is selected from Zr, Al, Na, K, Mg, Ca, Sr, Ni, Co, Ti, Sn, Mn, Cr, Fe, and V. and the coating layer is 0.1 to 10% of total weight amount. As a result, the structure stability is improved due to high fracture toughness of the coating layer.

Another method to increase cycle performance and power capability is described in US Patent 6796435[91], in which it claims that the cathode particle of a lithiated compound such as $LiCoO_2$ is coated with two layers of element. Each layer includes at least one coating element from Mg, Al, Ca, K, Na, Ca, Si, Ti, Sn, V, Ge, Ga, B, and As.

Besides coating cathode with metal oxide, doping metal elements is used in US Patent 7235193[92]. $LiCoO_2$ cathode particle optionally doped with Al is coated with amorphous complex lithium cobalt oxide with formula: $Li_{1+x}Co_{1-x}A_yO_2$, where $0\leq x\leq0.1$, $0\leq y\leq0.5$, and A is at least one selected from Al, B, Mg, Ca, Sr, Ba, Na, Cr, Gd, Ga, Fe, V, Ti, Sn, Mn, Zr, and Zn. The amount of coating layer has a mole ratio of 0.1 to 10 mol %. As a result safety, cycle life, and storage properties of the battery are improved.

4.1.2 $LiMn_2O_4$ Cathode Patents

Similar coating method is also used in synthesizing $LiMn_2O_4$ cathode to improve the cycle life and structure stability. In US Patent 6534217[93], it claims that $LiMn_2O_4$ cathode particle is coated with a layer of conductive oxide with general formula $Li_dMn_{2-e}C_eO_{4-f}$, where $0 \le d \le 1.5$, $0 \le e \le 1.5$, and $0 \le f \le 0.5$ C is at least one element selected from Al, Fe, Cu, Co, Cr, Mg, Ca, V, Ni, Ag, Sn, B, Ga, and an inner transition element. The conductive oxide layer has a quantity of 0.1 to 10% mol. As a result, the new battery cathode has prevented lithium from being deposited onto the positive electrode.

In US Patent 6884543[94], it claims that lithiated compound is doped with other metal elements. The general formula of the doped product is $Li_xMn_{2-y}Ma_yO_4$, where Ma consists of Zn, Co, Al, Sn, Cr, and Mg; $0.9 \le x \le 2$, and $0.01 \le y \le 0.5$. The mole ratio of dopants to manganese is within the range of 0.01/1.99 and 0.5/1.5. As a result, capacity retention is improved at elevated temperature.

US Patent 6040089[95] has claimed to use multi-doping of $LiMn_2O_4$ by other metal elements. The final product has a general formula of $Li_{1+x}Mn_{2-\gamma}M'_{m1}M'_{m2}\ldots M'_{mk}O_{4+z}$, where M'_{m1}, M'_{m2}, ...M'_{mk} are two different cations other than lithium and manganese selected from alkali, alkaline, and transition metals; x, y, m1, m2, …mk are between 0 and 0.2; m1, m2 and y are greater than 0; z is between -0.1 and 0.2; and equation $y=x+m1+m2+\ldots+mk$ and $3.3<\frac{m1V1+m2V2+\cdots MkVk}{M1+m2+m3+\cdots mk}<3.7$ (V1, V2,…Vk are valence states of cations M) need to be satisfied. As a result, the structure stability and cycle life are improved.

Surface treatment of $LiMn_2O_4$ cathode particle is proposed in US Patent 6489060[96], where

$LiMn_2O_4$ particle surface is deposited with a small amount of foreign metals whose atomic numbers are greater than 11. The final product is produced by heating a spinel structure compound and a foreign metal compound where the foreign compound decomposes to coat the spinel compound surface without entering the bulk structure. The foreign metal compound should incorporate Bi, Pb, La, Ba, Zr, Y, Sr, Zn, and Mg. As a result it has greatly suppressed capacity fading during cycling at elevated temperature.

4.1.3 $LiFePO_4$ Cathode Patents

US Patent 7338734[61] claims that the olivine compound cathode is doped with a low concentration of metal cations in lithium deficient stoichiometry ($Li_{1-x}M_xFePO_4$). The general formula is $Li_{1-a}M''_aFePO_4$, where M'' is the element selected from Mg, Al, Ti, Fe, Mn, Zr, Nb, Ta, and W in the form of metal oxide or metal alkoxide. As a result, it has increased the electronic conductivity at room temperature, consequently power density of the battery.

Doping metal cations in iron deficient stoichiometry is described in US Patent 6884544[97]. It claims that olivine compound is mixed with other metal materials. It has a general formula of $Li_aFe_{1-y}M_yPO_4$, where M is selected from at least one element from Be, Ca, Sr, and Ba and $0<y<1$. As a result, cycle life of olivine cathode is improved. The major difference between patent 6884544 and patent 7338734 is that the doping metal is substituted into M2 vacant site; where in previous patent, the doping metal is substituted into M1 vacant site.

Complex metal doping is used in US Patent 7371482[98]. The olivine structure $LiMPO_4$, where M is $Fe_xCo_yNi_zMn_w$ with $0 \leq x \leq 1$, $0 \leq y \leq 1$, $0 \leq z \leq 1$, $0 \leq w \leq 1$, and $x+y+z+w=1$, is manufactured in following steps:

(1) Provide a equimolar aqueous solution of Li^{1+}, Fe^{3+}, and PO_4^{3+} by dissolving iron nitrite;

(2) Heating the solutes at temperature below 500°C to form a pure homogeneous Li and Fe

phosphate precursor;

(3) Annealing the precursor at temperature at less than 600°C in an inert or a reducing atmosphere forming $LiFePO_4$ olivine structure with particle size less than 1um.

4.1.4 $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ Cathode Patents

After reviewing the patents related to $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathode, it is found that most of them are US application patents.

US Patent 2007/0292763[73] claims the manufacturing process for lithium molybdenum composite transition metal oxide. The compound has general formula $Li_{1+x}(Ni_{1/3}Co_{1/3}Mn_{1/3})Mo_yM_kO_{2-z}X_z$, where M includes at least one of Mg, Zn, Al, Ga, B, Zr, Si, Ti, Nb, and W; X includes at least one of F, S, Cl, and I; $0 \le x \le 0.33$, $0 \le y \le 0.2$, $0.01 \le k \le 0.15$, and $0 \le z \le 0.3$. It is made by mixing a metal transition precursor, molybdenum precursor, a lithium source, and a sintering agent, followed by thermal treatment of mixture to obtain a lithium molybdenum composite transition metal oxide. The metal transition precursor includes $Ni_{1/3}Co_{1/3}Mn_{1/3}M_kCO_3$, where M includes at least one of Mg, Zn, Al, Ga, B, Zr, Si, Ti, Nb, and k ranges from 0.01 to 0.15. The lithium salt is selected from lithium carbonate ect. The molybdenum additive is selected from compound consisting of MoO_3, $MoCl_3$, MoO_2, and mixture of them. Sintering agent is selected from compound consisting of LiF, LiCl, LiI, and mixture of them. As a result, the new cathode with higher tap densities has achieved a higher energy density and a better cycle life.

Another process for synthesizing cathode material having formula $Li_{1+\delta}Ni_xMn_{x+y}Co_{1-2(x+y)}M_yO_{2-a}P_a$, where M=Mg, Zn, Ca, Sr, Cu, and Zr; P=F, S; $-1/10 \le \delta \le 1/10$, $0 \le x \le 1$, $0 \le y \le 1/10$, $0 \le z \le 1/10$, $0 \le a \le 0.3$, is described in US Patent 2007/0111098[99]. it claims a The process includes mixing a metal precursor, an aqueous ammonia solution, and a basic solution to form a metal composite hydroxide, followed by reacting with a lithium precursor to form the final product. As a result, the new cathode exhibits improved cycle life with high discharge rate, good thermal stability, and high capacity.

In US Patent 2007/0212609[71], it claims that the $LiNi_xCo_yMn_zO_2$ cathode is combined with spinel type lithium manganese oxide with added with lithium cobalt oxide. Additive lithium cobalt oxide is doped with at least one of Mg and Al, and amount of doped lithium cobalt oxide added to the original cathode consists of 5-20% of the whole cathode weight. The cathode is further combined with spinel type lithium manganese oxide which consists of 30-50% of the whole cathode weight. As a result, thermal stability of a mixed cathode is enhanced.

4.2 Business Model

Choosing the right business model is vital for a start-up company. From the supply chain shown in Figure 27, three business options can be identified: licensing the patent to existing Li-ion battery manufacturers, being Li-ion battery manufacturer, and being car manufacturer producing electric vehicles integrated with Li-ion battery.

The intellectual property search has revealed the current status of Li-ion battery technology summarized in Figure 27. It is observed that the competition among Li-ion battery technologies is tight. Right now, no technology has clear advantages over the others. Therefore, battery manufacturing becomes the main focus for producers since it determines both product performance and cost which are the key factors for a start-up company to survive in the market[100]. As a result, licensing the patent to the battery manufacturer may not be the best strategy for commercializing a Li-ion battery technology. On the other hand, high initial investment, complex plant construction, uncertain vehicle technology and slow profit return suggest that building a manufacturing plant and producing the Li-ion battery integrated electric cars may not be feasible for a start-up company as well.

For above reasons, the proposed business model is to manufacture Li-ion battery with available raw materials outsourced in global market. Cell assembly which includes battery packaging and mandatory protection circuit installation are included in the manufacturing plan. Based on battery supply chain shown in Figure 28, the primary customers are the electric vehicle manufacturers mainly producing PHEVs and BEVs.

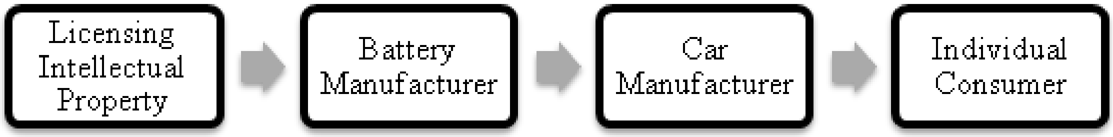


Figure 27 Battery Supply Chain for Automotive Industry

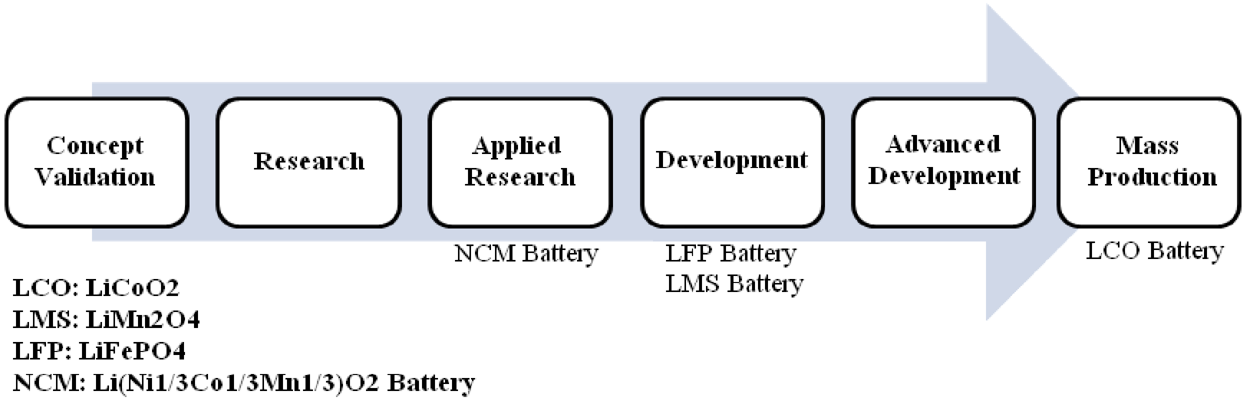


Figure 28 Li-Ion Battery Technology Status

4.3 Lithium Ion Battery Cost Analysis

Generally manufacturing cost consists of variable cost (material cost, labor cost, electricity cost, and yield adjustment) as well as fix cost (machine amortization, building amortization, and overhead cost) are taken into consideration in the cost model.

4.3.1 Material Cost

Because of confidentiality and tight competitiveness, most of the Li-ion battery manufacturers are unwilling to disclose their battery material costs. Due to this reason, a bottom up approach is used to estimate the material cost per cell based on the previous study by Linda Gaines and Roy Cuenca[101] in 2000. A few assumptions have been made as follows:

(1) All Li-ion batteries have total energy of 425Wh/cell.

(2) Amount of anode, binder, current collector, and carbon used is proportional to that of cathode used in one cell.

(3) According to the report by Research and Markets in 2009[102], $LiCoO_2$ cathode material costs \$50/kg, while $LiFePO_4$ cathode material costs \$28/kg. Furthermore, CleantechGroup[103] has indicated that material costs of $LiMn_2O_4$ and $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathodes are competitive to those of $LiFePO_4$ and $LiCoO_2$ cathodes. Therefore, it is assumed that $LiMn_2O_4$ and $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathodes cost \$28/kg and \$50/kg.

Results in Figure 29 shows that $LiCoO_2$ battery is the most expensive among all the batteries due to its expensive cobalt in the cathode. Although $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ cathode is expected to be expensive due to complicated synthesis process, its high energy density makes the total material cost per cell the cheapest since less cathodes are needed in one cell to provide the same amount of energy. Similarly, the cost for $LiMn_2O_4$ battery is higher than that of $LiFePO_4$ battery due to its low energy density. It is worth to note that another component which results in comparable cost as cathode is electrolyte. This is due to the fact that most of the electrolytes use fluorine based lithium salts. And the price of lithium salts is quite expensive (details of Li-ion battery material costs are listed in Appendix C).

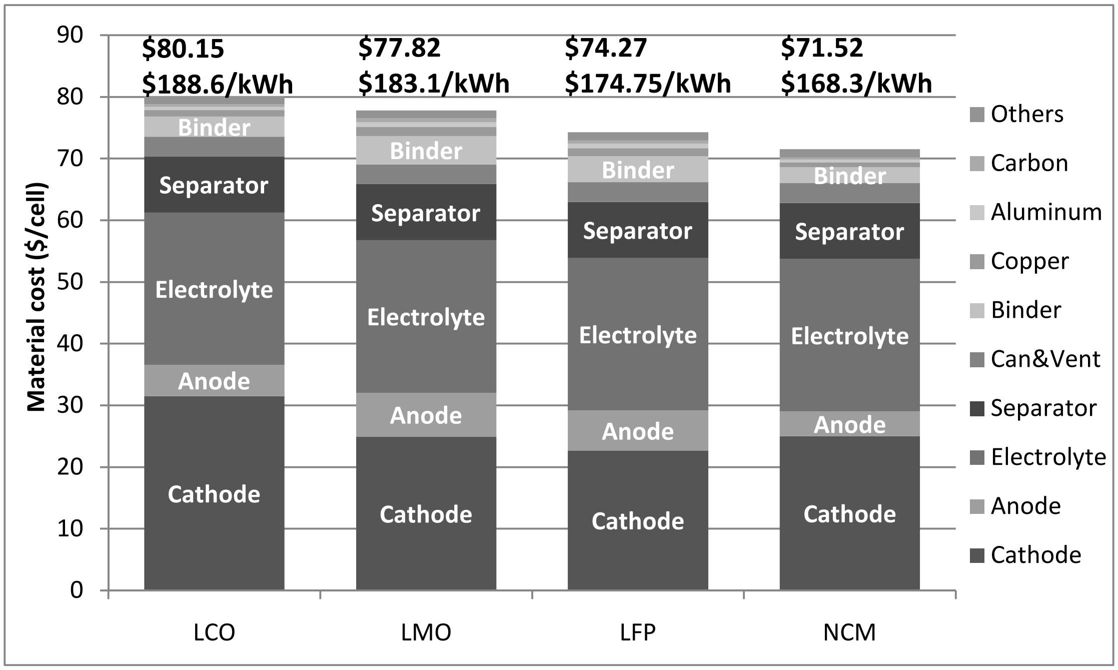


Figure 29 Material Cost Break Down

4.3.2 Manufacturing Cost

According to the study by Linda Gaines and Roy Cuenca from Argonne National Laboratory in 2000[101], mainly three processes are involved in battery manufacturing: cathode/anode production, battery cell production, and battery module and pack integration (battery manufacturing process is shown in Appendix D). Except cathode particle synthesis, the overall battery manufacturing processes are similar for all types of Li-ion batteries.

Battery manufacturing starts with cathode/anode productions which are similar to each other. Cathode active particles with synthesis steps described in section 2.1 are mixed with binder, solvent, and other additives to make a paste. Then the mixture is coated onto the aluminum foil in the coating process. Anode material such as graphite paste is coated onto the copper foil in a similar way. Coated electrodes are dried up afterwards. Calendaring process is carried out to ensure the uniformity of electrode thickness. Electrode foils are then trimmed into desired size, and wound up with separators in between. Battery connection is built by tabs welded on cathode and anode followed by wetting process in which electrodes and separators are inserted into canister filled with electrolyte. Lastly, ancillary components such as vents and safety devices are attached to complete an individual cell production. Battery module is assembled by packaging numbers of individual cells together. Plastic case is chosen for battery module because it is inexpensive and light-weighted. Therefore, manufacturing cost break down of Li-ion batteries based on a large plant scenario can be estimated shown in Figure 30 and Table 15 (details of manufacturing cost are shown in Appendix E) with following assumptions which are considered reasonable as:

(1) One Li-ion battery production line is able to produce 250,000 cells/year/shift[104]. Plants with various capacities are shown in Table 14.

Plant size	Number of production line	Capacity(cells/yr/2 shifts)
Small	4	1000000
Medium	8	2000000
Large	12	3000000

Table 14 Plant Capacity

(2) Total manufacturing yield is 95%.

(3) Unit labor costs \$20/hour with total working time 4320 hours/year[105].

(4) Industrial electricity price is \$0.07/kWh[106].

(5) Machines cost \$630,000 with total power consumption 20.02kW per production line.

(6) Factory building has an area of 1000m^2 with costs \$1000/m^2[107]

(7) Operation durations for machine and building are 20 years and 50 years. For amortization cost per year, 10% interest rate is assumed.

(8) Overhead fix cost which includes cost for R&D, marketing, and engineering is assumed to be \$7/cell time full production capacity.

(9) Material cost reduction with 2.5% of initial cost is assumed for every 1000000 cells

produced.

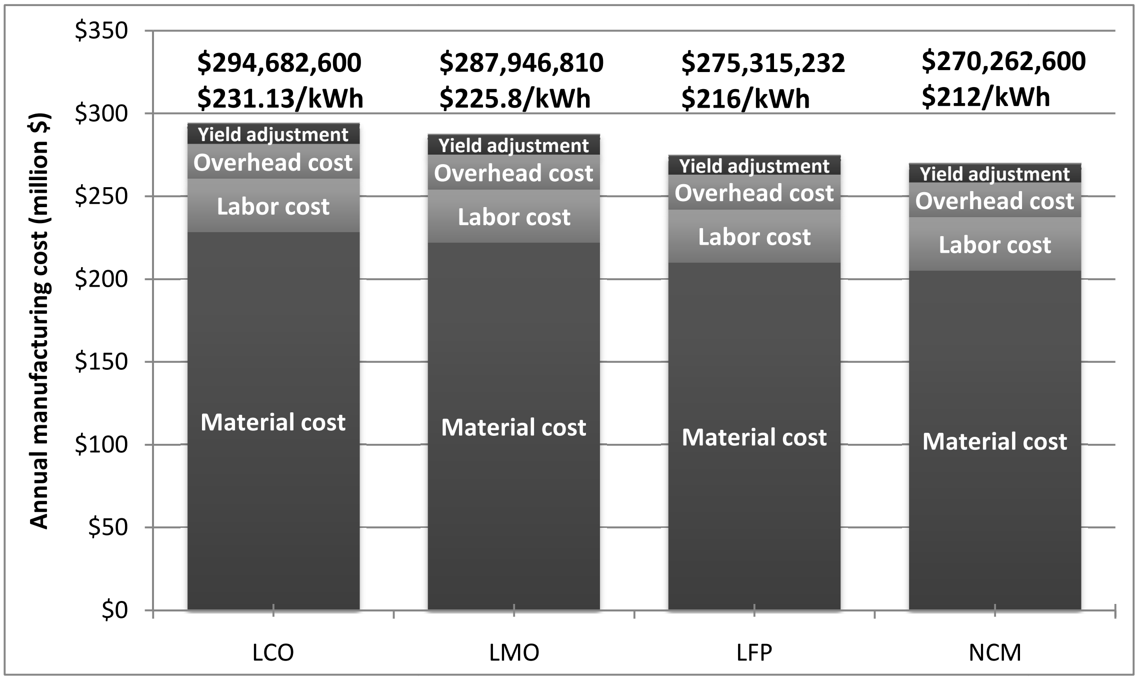


Figure 30 Total Annual Manufacturing Cost at Large Plant Scenario

Battery type	Cell cost	Cell cost
$LiCoO_2$	$98.23	$231.13/kWh
$LiMn_2O_4$	$95.98	$225.8/kWh
$LiFePO_4$	$91.77	$216/kWh
$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$	$90.09	$212/kWh

Table 15 Overall Manufacturing Cost

It is observed that the major component driving the total manufacturing cost is material cost. It consists of more than 76% of the overall cost. Based on the previous material cost breakdown analysis, future research needs to focus on developing low cost cathode, anode, electrolyte, and separator meanwhile increase battery energy density to significantly lower the cost. For example, 30% of cathode cost reduction can significantly lower the total cell cost as shown in Figure 31. Furthermore, yield adjustment contributes 4% of the overall cost. It represents the extra cost due to cells which fail to meet the quality requirement. Hence, enhancing manufacturing process is the key to eliminate the unnecessary expense.

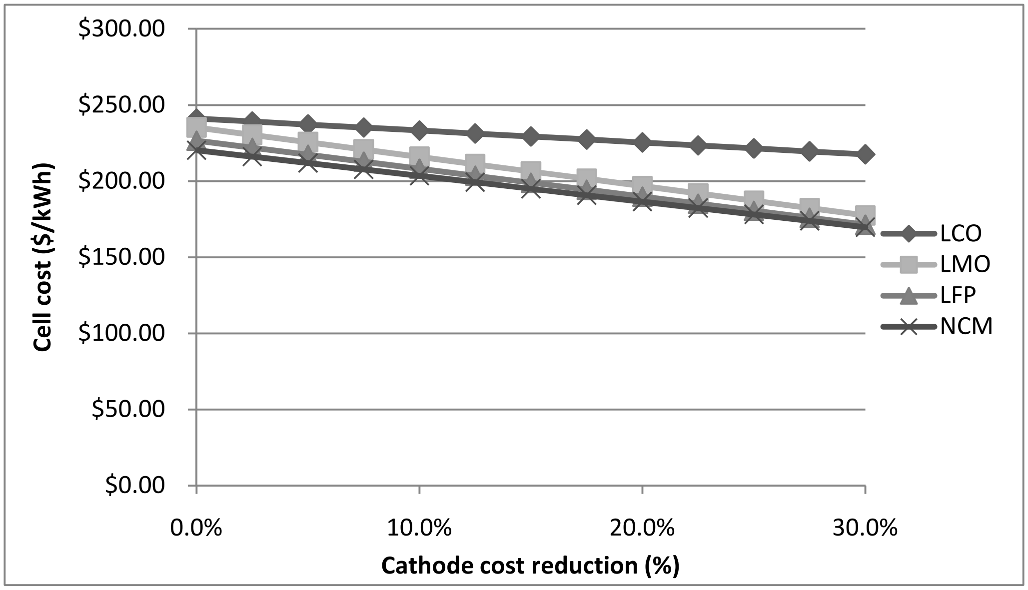


Figure 31 Sensitivity Analysis of Cell Cost to Cathode Cost Reduction

Besides above approach, economy of scale is another effective way to achieve battery cost reduction. However, for Li-ion batteries, the economy of scale is limited above certain production volume due to small contribution from fix cost. Figure 32 shows $LiFePO_4$ battery economy of scale with different plant sizes. In order to gain maximum profit, building the plant with appropriate size is essential. For example, if annual production volume is expected to be less than 2 million, building a large plant would result in a higher unit cost compared to a medium sized plant. Thus it is necessary to have an accurate estimation of market demand in order to minimize the loss from over sizing, which in turn depends on the utility analysis for different batteries. The following section will be on battery utility analysis for PHEV and BEV, followed by the market demand analysis.

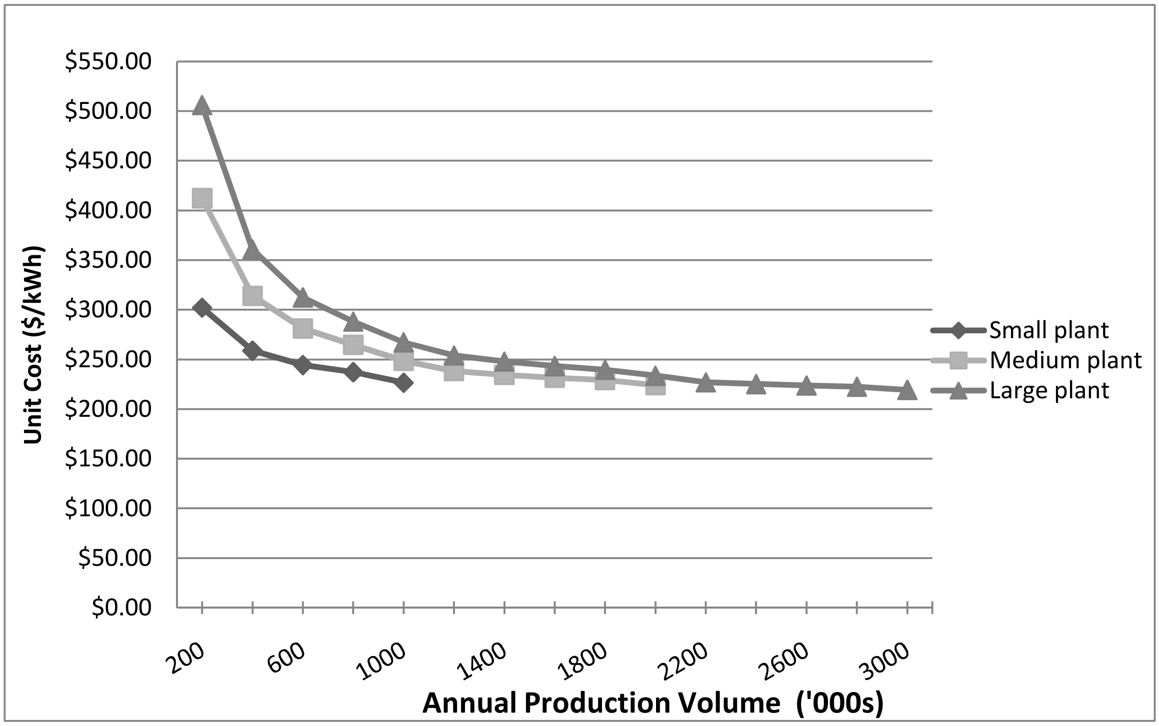


Figure 32 Economy of Scale of $LiFePO_4$ Battery

4.4 Lithium Ion Battery Utility Analysis

Five factors employed to assess Li-ion battery technologies in chapter 2.1 are extracted from the requirements established by USABC[108]. They will be used as the benchmark to assess Li-ion battery utility in PHEV and BEV markets respectively. In addition, PHEV with 40 mile electric drive and BEV with 100 mile electric drive are taken in the analysis.

4.4.1 Lithium Ion Battery for PHEV

Characteristics	Units	40-mile PHEV
CD mode power rate	kW	10
CD mode power density	W/kg	83.3
CD mode total energy	kWh	11.6
CD mode energy density	Wh/kg	96.67
CD mode power/energy		0.86
CS mode total power	kW	38

CS mode power density	kW/kg	316.6
CS mode total energy	kWh	0.3
CS mode energy density	Wh/kg	2.5
Maximum Weight	kg	120
Calendar Life	years	15
Cycle Life(CD) 80% capacity retention	cycles	2300
Cycle Life (CS) 80% capacity retention	cycles	150,000
Upfront Cost with production 100k/yr	$/kWh	$293

Table 16 PHEV Battery Requirements

(a) Power and energy densities

A 40-mile PHEV generally requires battery with a low power to energy ratio because it focuses on electric drive. Based on the calculation in section 2.1, power and energy densities for four types of Li-ion batteries are summarized in Figure 33. The result shows that currently all Li-ion battery technologies are able to satisfy the PHEV power and energy density requirements.

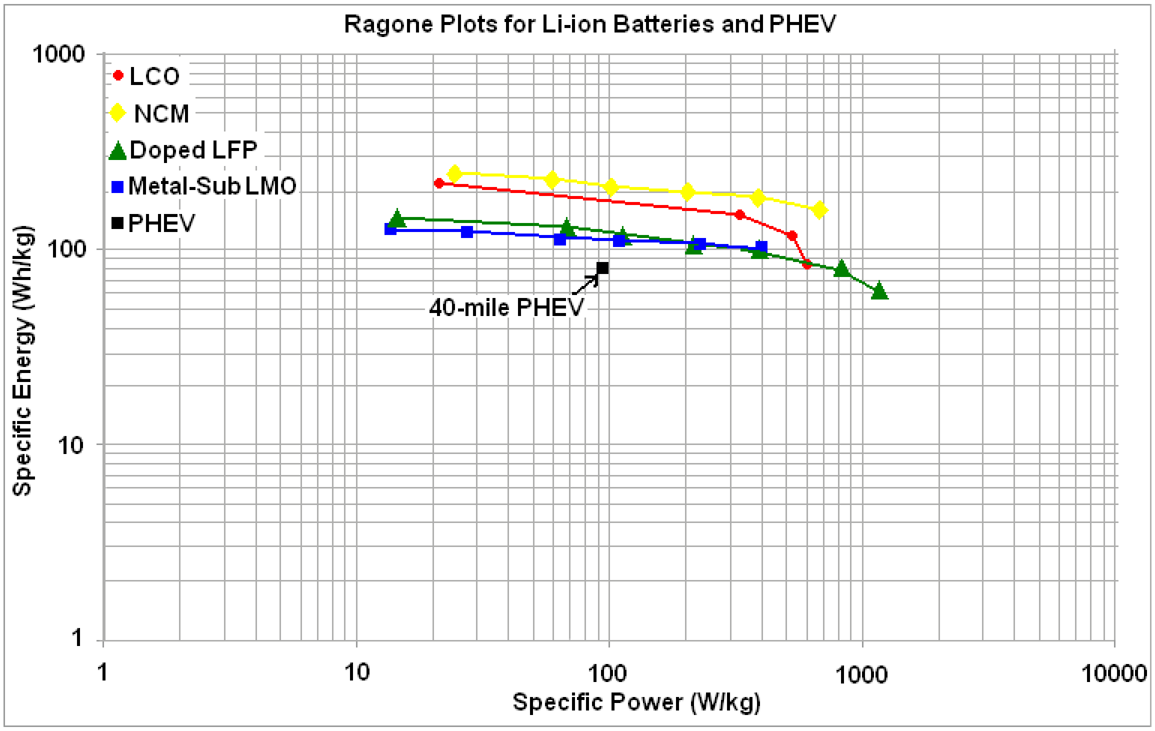


Figure 33 Ragone Plots of Li-ion batteries for PHEV

(b) Safety

In general, safety is a less concern for batteries in consumer electronics since they only require small amount of cathodes for their low power and low energy operation. However, for high power and high energy applications such as electric vehicles, thermal behaviors are extremely important in evaluating Li-ion batteries in addition to their electrochemical performance and economy[109]. Especially when large amount of cathodes are involved in PHEV battery, safety must be ensured to avoid overheating or overcharging which will cause the battery to break down and release oxygen. This may lead to catastrophic explosion.

As discussed in section 2.1.1, $LiCoO_2$ battery suffers from severe thermal runaway. There have been a few explosion cases from SONY $LiCoO_2$ battery showing that even with protection circuits, disaster is still unavoidable. Therefore, safety problem could impede $LiCoO_2$ battery application in PHEV. With reduced content of cobalt, $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ shows an improved safety. According to the report by Cleantech[103], $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ battery only starts to catch fire at 200°C while $LiCoO_2$ battery starts at 140°C. However, the safety for this cobalt and nickel oxide based battery is still unproven for automotive application, especially in long range electric drive PHEV. Thus, there is a high risk for this battery to meet the safety requirement.

On the other hand, $LiMn_2O_4$ and $LiFePO_4$ batteries have been proved with stable oxidation states which reduce chances of thermal runaway. In fact, study by Paul Wuebben et al[110] has shown that the thermal tolerance follows the order as:

$LiFePO_4 > LiMn_2O_4 > Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2 > LiCoO_2$

Furthermore, electronic companies such as ST Microelectronics have already developed battery management chips (Bipolar-CMOS-DMOS) to accurately control the battery charging and discharging cycles. Various battery companies have already demonstrated that with battery management system, $LiMn_2O_4$ battery is able to provide a reliable operation[48, 60]. Therefore, both $LiMn_2O_4$ and $LiFePO_4$ batteries can offer better alternatives in terms of safety.

(c) Durability

When PHEV operates in CD mode, it requires the battery to perform in a wide SoC window, though operating in wide SoC window will normally degrade battery capacity over cycling[18]. This will ensure most of the energy stored will be depleted for the electric drive. In addition, at least 80% of capacity should be obtained after 2300 cycles which secures sufficient power and energy can be delivered by the battery. On the other hand, for PHEV operates in CS mode, a narrow SoC window is sufficient since CS mode does not require any electric driving. Therefore battery durability in CD mode is more critical than that in CS mode. For this reason, durability in CD mode is assessed in this section. To calculate capacity retention rate after cycles of operation, it is assumed that capacity loss is in a linear function with operation cycles.

The results are summarized in Figure 34 in which above the target is desired (details of calculation are shown in Appendix F). At current stage, with 0%-100% SoC window, severe capacity loss is observed after less than 1000 cycles of operation for both $LiCoO_2$ and $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ batteries. This could lead to malfunctions of electric vehicles. $LiMn_2O_4$ battery has an improved cycle performance and it is able to achieve 43% of its initial capacity after 2300 cycles of operation. 80% of capacity could be obtained for $LiFePO_4$ battery under the same condition.

To improve cycle performance, controlling SoC window is applied without modifying battery chemistry. A 20%-90% SoC window is recommended[5] for the battery implemented in PHEV. But the trade off is that the energy delivered is reduced to 70% of total energy stored. Another method to improve cycle performance is to replace common graphite anode with $Li_4Ti_5O_{12}$ anode. This approach will improve the safety as well as durability. But $Li_4Ti_5O_{12}$ anode will reduce the operation voltage, and further reduce power and energy densities[18].

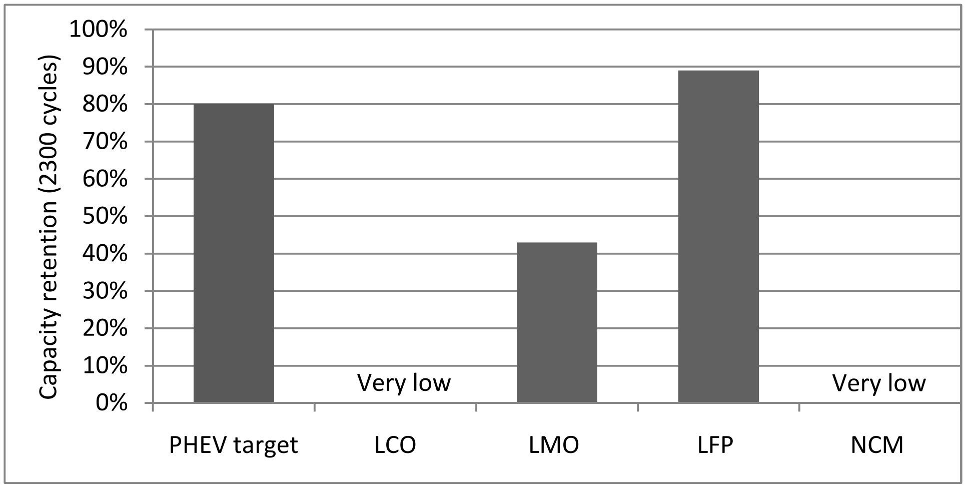


Figure 34 Li-ion Batteries Cycle Performance in 40-mile PHEV

(d) Cost

For $LiCoO_2$, $LiMn_2O_4$, and $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ batteries to operate reliably after desired numbers of cycle, 10%-90% SoC window is assumed in the calculation. Consequently, oversize battery packs are used for them in order to deliver same amount of energy. The cost target for PHEV battery pack is $294/kWh. Assuming a large plant scenario with production volume at maximum production capacity, the battery cost for a 40-mile PHEV is summarized in Figure 35 in which below the target is desired (calculations are shown in Appendix G). The manufacturing cost of $LiCoO_2$ battery pack is the highest among all which is 1.37 times the cost target without any gross margin. It indicates that current $LiCoO_2$ battery is too expensive for PHEV application. On the other hand, it is highly likely for the other 3 types of Li-ion batteries to meet the cost target in near future, if material cost, yield adjustment can be further reduced with enhanced durability.

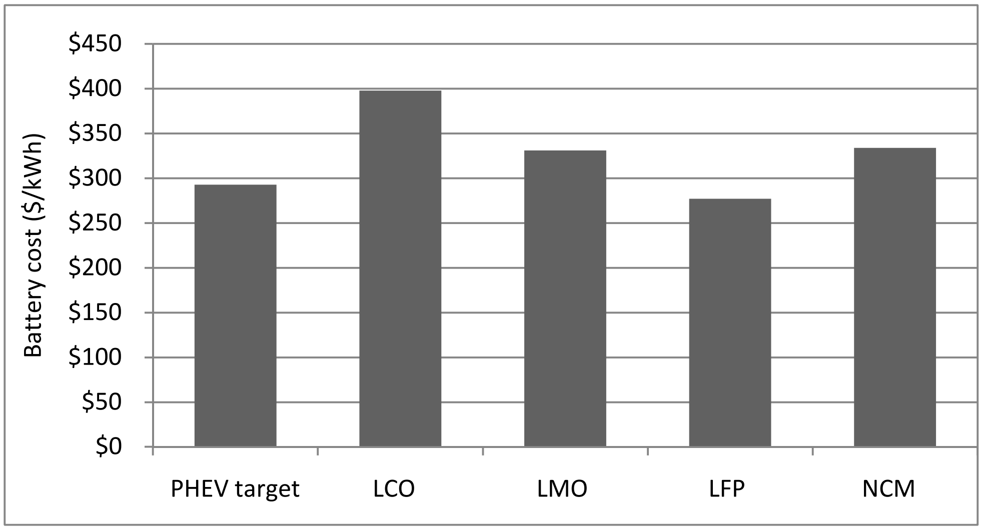


Figure 35 40-mile PHEV Battery Cost.

4.4.2 Lithium Ion Battery for BEV

In the year 2005, USABC has published a minimum and an ideal long-term commercialization goals for BEV battery shown in Table 17[108].

Characteristics	Units	Min	Ideal
Max power	kW	60	80
Max power density	W/kg	300	400
Operational power	kW	10	13.3
Operational power density	W/kg	50	66.67
Total Energy at C/3 rate	kWh	30	40
Energy Density at C/3 rate	Wh/kg	150	200
Operational power/energy ratio		0.33	0.33
Maximum Weight	kg	200	200
Calendar Life	years	15	15
Cycle Life 80% capacity retention	cycles	1000	1000
Upfront Cost	$/pack	N.A.	N.A.
Cost	$/kWh	150	100

Table 17 USABC Battery Goal for BEV

(a) Power and energy densities

For battery application in BEV, its high energy density is more favorable than high power density since energy storage capability directly determines BEV driving distance. Again, based on the calculation in section 2.1, Li-ion battery power and energy densities are summarized in Figure 36. The result shows that present Li-ion batteries are able to meet the minimum power and energy density requirements. Considering long term ideal target, $LiMn_2O_4$ and $LiFePO_4$ could satisfy 90% of the requirement in energy density meanwhile providing sufficient power density. Furthermore, with technology development trend shown in Figure 3, there is a high probability for manganese and phosphate based batteries to meet the ideal requirement.

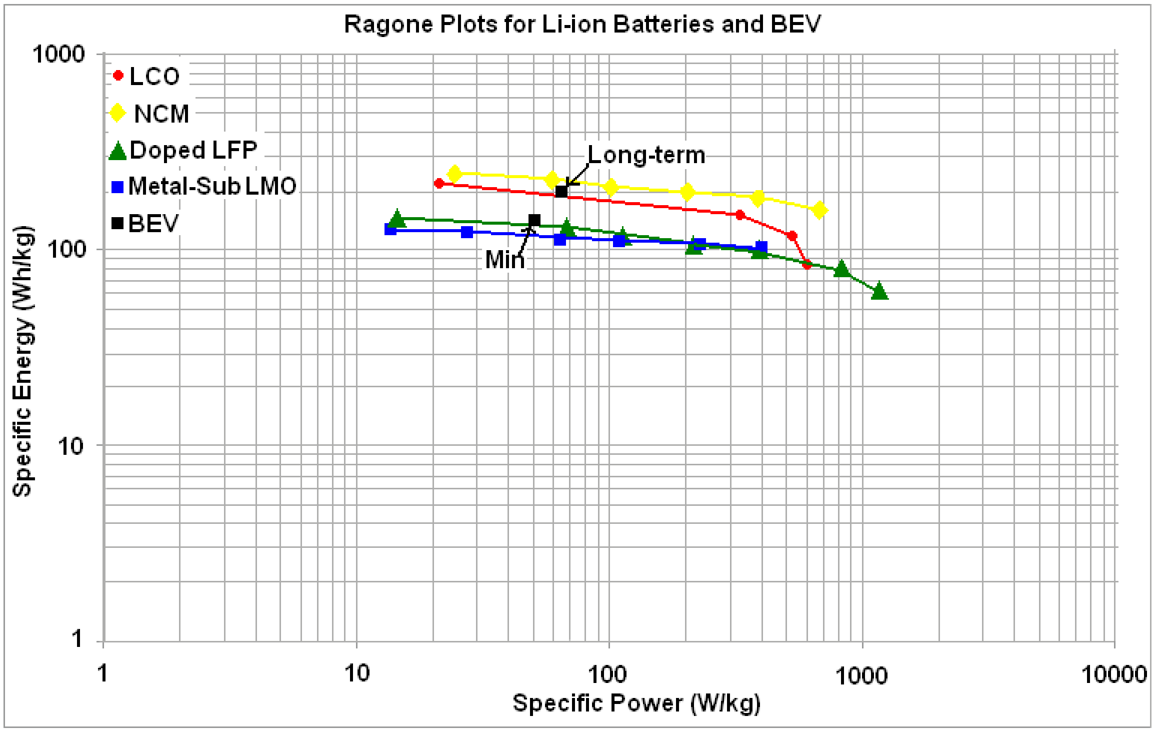


Figure 36 Ragone Plots of Li-ion batteries for BEV

(b) Safety

Since batteries are supplying all the energy for BEV operation, large amount of cathodes are used in the battery pack. If cathodes are potentially unstable, more heat will be generated during exothermic reactions, and chances of BEV battery pack to catch fire are much higher than that for PHEV. For this reason, current cobalt and nickel batteries may not be applicable to BEV.

Similarly, with unique battery management circuit, manganese and phosphate batteries offer better choice due to their relatively higher thermal tolerance.

(c) Durability

BEV batteries need to run in a wide SoC window with capacity retention of 80% after 1000 cycles. Same method is used to assess batteries durability in BEV. Results have proven that 75% capacity retention can be achieved by $LiMn_2O_4$ battery and 95% by $LiFePO_4$ battery. Both $LiCoO_2$ and $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ batteries are not able to obtain required capacity after 1000 cycles as displayed in Figure 37.

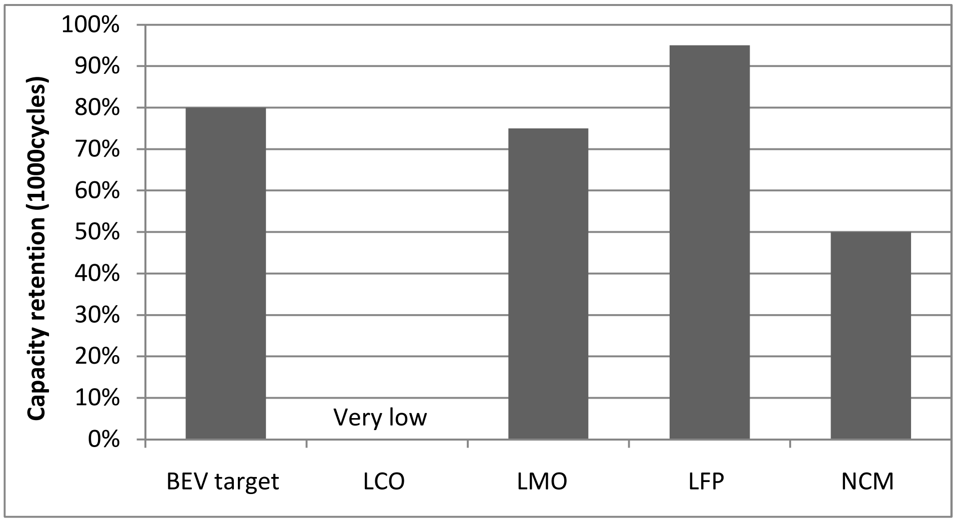


Figure 37 Li-ion Batteries Cycle Performance in BEV

(d) Cost

Minimum cost target set by USABC is \$150/kWh, and ideal case is \$100/kWh. According to the previous durability assessment, both $LiMn_2O_4$ and $LiFePO_4$ batteries may not need to be oversized for BEV application. By applying the same approach, battery cost for BEV is summarized in Figure 38 (calculations are shown in Appendix G). The result has shown that current battery cost is much higher than the cost target. Compared with results in PHEV, it can be concluded that a higher energy requirement has imposed a higher risk for battery commercialization, furthermore there is no clear method to reduce the cost significantly in near future.

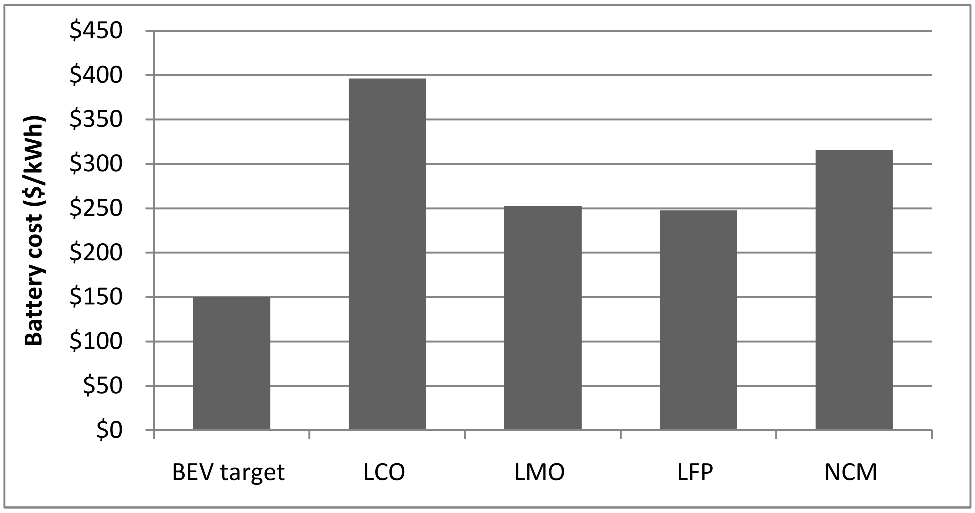


Figure 38 BEV Battery Cost

4.4.3 Conclusion

Table 18 shows the utility summary for all four types of Li-ion batteries. At current stage, $LiCoO_2$ battery may not be suitable for both PHEV and BEV applications due to its unsolved safety problem, and low durability. It has not been proven yet whether $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ battery is able to deliver a safe operation for PHEV, but it is highly unlikely to be applicable in BEV, since exothermic reaction still takes place at 200°C. In addition, its poor durability has not been solved so far. Compared with above batteries, $LiMn_2O_4$ and $LiFePO_4$ batteries have a lower risk to be commercialized in PHEV and BEV. They have exhibited higher durability and safer operations. However, the main barrier is cost. Especially for BEV application, to achieve its ideal cost target remains extremely challenging. As a result both $LiMn_2O_4$ and $LiFePO_4$ batteries are potentially more suitable for PHEV and BEV. Moreover, $LiFePO_4$ battery has demonstrated a slight advantage over $LiMn_2O_4$ battery in terms of durability and cost. Therefore, $LiFePO_4$ battery is chosen for the further analysis while taking $LiMn_2O_4$ battery as the major competitor.

PHEV	LCO	LMO	LFP	NCM	PHEV target
Battery power density (W/kg)	328	123	124.2	204	83.3
Battery energy density (Wh/kg)	164	123	124.2	204	96.67
Safety	Poor	Proven	Proven	Unproven	Proven
Durability (capacity retention 2300 cycles)	Low	43%	89%	Low	80%
Battery cost ($/kWh)	$398	$331	$276.90	$334	$293
BEV					BEV target
Battery power density (W/kg)	328	64.4	68.25	107.7	50
Battery energy density (Wh/kg)	164	128.7	136.5	215.4	150
Safety	Poor	Proven	Proven	Unproven	Proven
Durability (capacity retention 1000 cycles)	Low	75%	95%	50%	80%
Battery cost ($/kWh)	$396.20	$252.75	$247.78	$315.32	$150

Table 18 Li-ion Battery Utility Summary

4.5 Market Demand and Manufacturing Strategy

Current phosphate based technology has reached the development stage for the automotive application According to battery development process suggested by Dr Ralph J. Brodd in 2005[111], it takes another 5 to 9 years for $LiFePO_4$ battery to be mass adopted in electric vehicles. Hence, the manufacturing plant will be built at beginning of year 2015 to supply batteries for US and European automakers. By the time, the total demand will reach 752,000 units for PHEV and 377,000 units for BEV predicted by DeutscheBank[19]. Demand for $LiFePO_4$ battery is based on its competitiveness from car manufacturer's point of view, and it is driven by the product utility. Three major utilities energy density, durability, and price are selected to calculate multi-attribute utility for both $LiFePO_4$ and $LiMn_2O_4$ batteries based on the utility model developed by Professor Joel Clark's group. Manganese oxide battery produced by LG Chem has the price of $625/kWh[112]. Combined with its energy density and durability discussed in the previous section, the multi-attribute utilities for $LiMn_2O_4$ battery are estimated to be 0.59 in PHEV market and 0.6 in BEV market. Meanwhile, $LiFePO_4$ battery multi-attribute utility is varied with unit price for both PHEV and BEV markets shown in Figure 39 and Figure 40 (details of multi-attribute utility are shown in Appendix H). In order to make maximum profits with a significant market penetration, pricing strategy has been proposed for $LiFePO_4$ battery manufacturer as follows:

(1) A low price is set to be $250/kWh which is equivalent to $107/cell. This will give utilities of 0.923 and 0.867 higher than its competitor 0.5925 and 0.599 in PHEV and BEV markets.

(2) A high price is set to be $500/kWh which is equivalent to $213/cell. This will keep the battery staying competitive to its counterpart with utilities of 0.81 and 0.7344 in PHEV and BEV markets.

Consequently, the probability of market penetration is summarized in Table 19. Further applying Decision Analysis Model developed by Frank Field in 1998, the final recommended manufacturing strategy is to build a medium plant, and sell the battery at high price which will give a net present value of $791,131,407 as profit return on investment shown in Table 20.

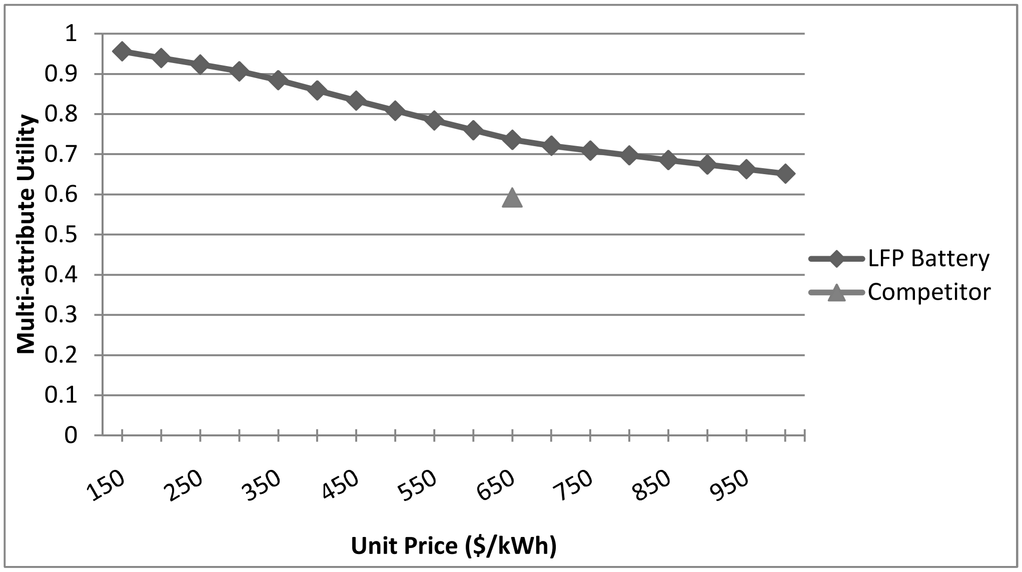


Figure 39 $LiFePO_4$ Battery Multi-attribute Utility for PHEV Application

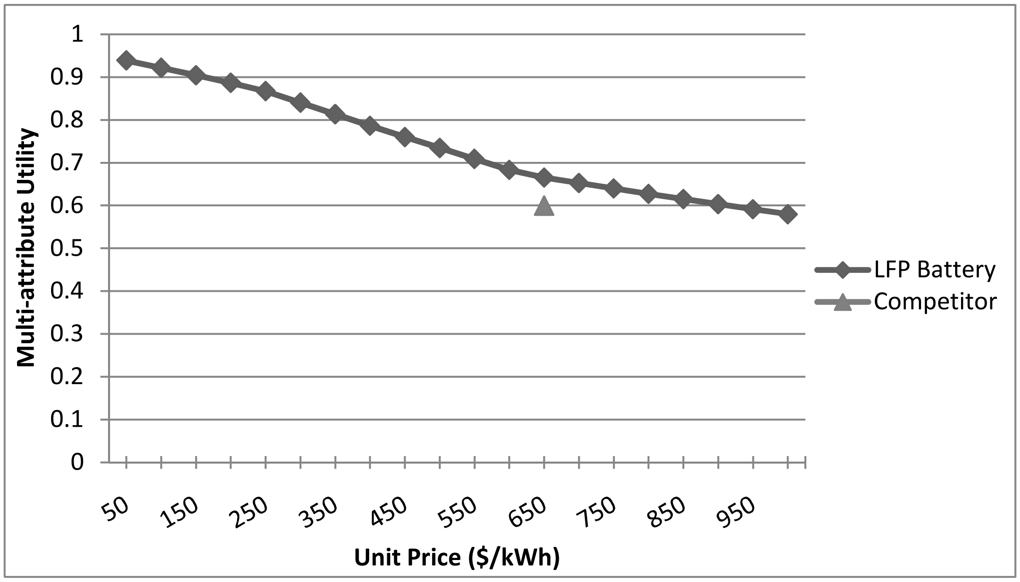


Figure 40 $LiFePO_4$ Battery Multi-attribute Utility for BEV Application

Total market at 2015 (cells)	52,740,000	
Market share	Probability at low price	Probability at high price
Low (1%)	35.00%	70.00%
Medium (2%)	45.00%	20.00%
High (3%)	20.00%	10.00%

Table 19 Estimated Market Share at Different Price Scheme

Total Plant Capacity	2000000
Annual Production	1,582,200
Piece Cost	$104.5558
Plant Size	Medium Scale
Price	$213/cell
NPV	$791,131,407

Table 20 Manufacturing Strategy for Period One

4.6 Implementation Effectiveness Analysis

Due to expensive Li-ion battery packs, both PHEV and BEV are expected to have higher upfront costs compared with gasoline counterparts, but lower operation costs and less CO_2 emission are the key incentive for their commercialization. Hence economical values of PHEV and BEV with $LiFePO_4$ battery packs are presented in this section in order to quantify the Li-ion battery implementation effectiveness. Net present value (NPV) is used to identify the impact of key variables such as battery pack cost reduction, daily mileage, gasoline price, and government subsidization on end-user's decision of purchasing PHEV and BEV. Current HEV is included in the comparison. All the models discussed in this section are based on current situations in U.S.

4.6.1 Electric Vehicle Model

All the vehicles including gasoline car, HEV, PHEV, and BEV are sedans with similar capacities for a standardized comparison. $LiFePO_4$ battery is used as energy storage for PHEV and BEV with price of $213/cell obtained from previous section(calculations of battery pack cost are in Appendix H). A 2009 Chevrolet Malibu hybrid sedan is chosen as HEV model with open market value (OMV) $25,555 and average fuel efficiency 30 mpg[113]. $1,550 tax credit is provided upon purchasing[114]. PHEV sedan with specifications similar to Chevy Volt[115] is summarized in Table 21. By assuming electric driving range is proportional to effective energy drawn from battery pack, an estimated specifications for BEV sedan is summarized in Table 22[116].

40-mile PHEV	
Electric drive (mile)	40
CS mode mpg	50
Average speed (mph)	50
Battery charging voltage (V)	120
Battery charging current (A)	15
Battery charging power (kW)	1.8
Battery charging energy (kWh)	8.8
Battery charging time (hour)	5
Vehicle cost	$30,000
$LiFeO_4$ Battery cost	$8,307
PHEV OMV	$38,307

Table 21 40-mile PHEV Specifications

BEV	
Electric drive (mile)	100
Battery effective energy (kWh)	22
Average speed (mph)	31
Battery charging voltage (V)	120
Battery charging current (A)	30
Battery charging power (kW)	3.6
Battery charging energy (kWh)	22
Battery charging time (hour)	6.2
Vehicle cost	$25,000
$LiFePO_4$ Battery cost	$18,318
BEV OMV	$43,318

Table 22 BEV Specifications

Lastly, to calculate the NPV for all three electric vehicles, a 2009 Chevrolet Malibu is chosen with OMV of $22,325 and average fuel efficiency of 26 mpg[117].

4.6.2 Topology

Three key factors are identified as daily mileage, gasoline price, and government subsidizations. Sensitivity of NPV to one factor is calculated while fixing the other two. Assumptions used in the model are shown as follows:

(1) Every vehicle has 10 years life time. By operating the battery in 90% to 20% SoC window, more than 80% of capacity is obtained after 10 years operation which is equivalent to 3650 cycles.

(2) Daily mileage is 50 miles.

(3) All electric vehicles are operating on one charge per day basis.

(4) Electricity price is $0.07/kWh[106].

(5) Gasoline price is $2.65/gallon[3].

(6) Vehicle exercise tax is 2.5%[118].

(7) Assume interest rate in NPV calculation is 2.5%.

(8) CO_2 emission for all vehicles are shown in Table 23[119]:

	CO2 emission (kg/mile)
Gasoline car with 26mpg fuel efficiency	0.348
HEV with 30 mpg fuel efficiency	0.312
PHEV in CS mode with 50mpg fuel efficiency	0.204

Table 23 Vehicle CO_2 Emission

Equations used in the model are shown below:

$$\mathrm{Premium\ cost} = \mathrm{XEV\ total\ cost} - \mathrm{gasoline\ car\ upfront\ cost}$$

Equation 4 Premium Cost to Purchase an XEV

$$\mathrm{HEV\ OC} = \frac{D_T}{\mathrm{mpg}} \times P_G$$

Equation 5 HEV Operation Cost

$$\mathrm{PHEV\ OC} = P_E \times E_D + \frac{(D_T - 40)}{\mathrm{mpg}} \times P_G$$

Equation 6 PHEV Operation Cost

$$\mathrm{BEV\ OC} = P_E \times E_D$$

Equation 7 BEV Operation Cost

Annual saving or income:

$$\mathrm{Annual\ saving} = \mathrm{XEV\ AOC} - \mathrm{gasoline\ car\ AOC}$$

Equation 8 XEV Annual Saving

NPV for XEV is calculated as:

$$\mathrm{NPV} = -\mathrm{Premium\ cost} + \sum_{n=1}^{10} \frac{\mathrm{Annual\ Saving}}{(1 + r)^n}$$

Equation 9 NPV Calculation

XEV: electric vehicles including HEV, PHEV, and BEV

OC: operation cost

AOC: annual operation cost

P_E: electricity price

E_D: daily energy consumption in electric drive

D_T: daily driving distance

P_G: gasoline price

r: interest rate

4.6.3 Implementation Discussion

In most of the countries, the amount of government rebate on future PHEV and BEV is not clear yet. It has been reported that the U.S. government has established a new policy, under which the PHEV with at least a 4-kilowatt-hour battery pack will be eligible for a $2,500 credit, with an additional $417 for each additional kilowatt-hour of battery capacity, up to $7,500. And a PHEV with 40 miles electric drive will most likely to enjoy the maximum credit[120]. If the policy is also applicable to BEV, then upon 40 miles electric drive with $7500 tax credit, a 100 mile BEV will enjoy $13,000 tax credit[120]. By applying the topology, NPV of $4624.57 and $3147.48 will be obtained for BEV and PHEV after 10 years of operation (calculation details are shown in .Appendix I). However, since government subsidization is normally limited to a certain number of buyers[114], following analysis is carried out to evaluate the economical values of PHEV and BEV without any government subsidization.

Battery cost reduction

Figure 41 show the sensitivity of NPV to battery cost reduction. Both PHEV and BEV are not cost effective to private user unless battery cost reduction of 43.75% and 50% are achieved for PHEV and BEV which is not likely to happen in near future. Generally, BEV is more sensitive than PHEV in this case since the battery pack consists of 41% of the total BEV cost as displayed in Figure 42.

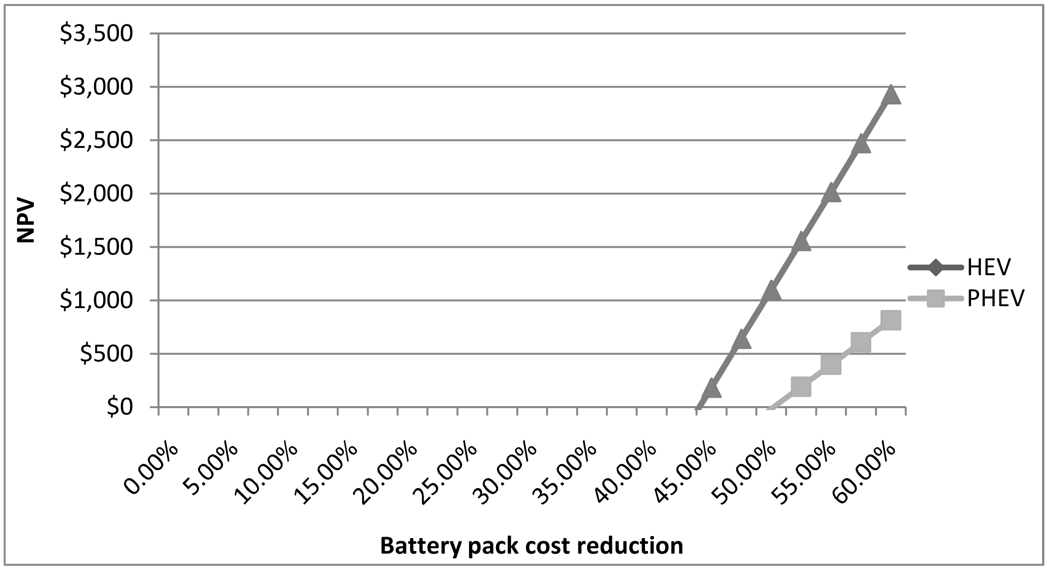


Figure 41 Sensitivity of NPV to Battery Cost Reduction without Government Tax Credits

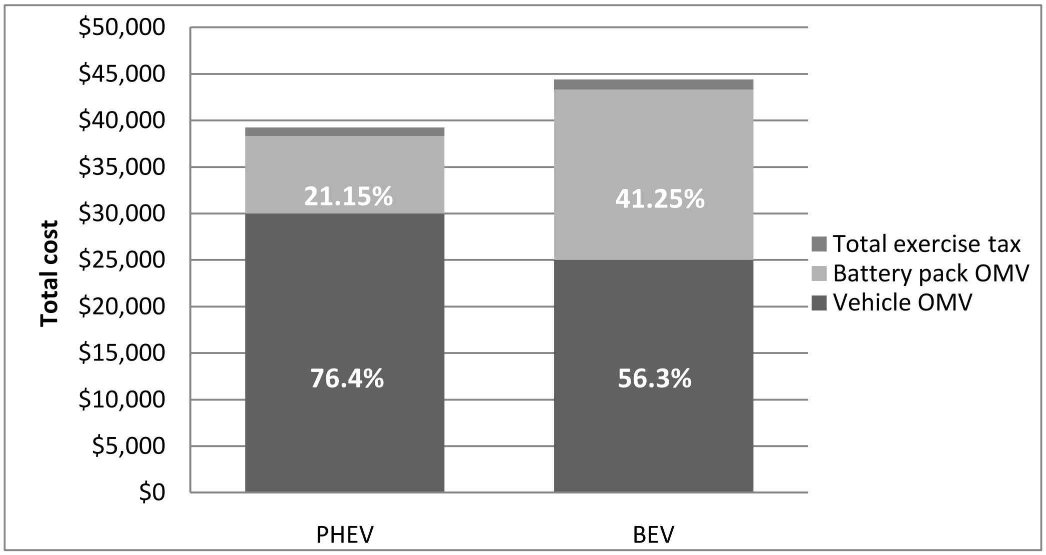


Figure 42 PHEV and BEV Cost Break Down

Daily mileage

Figure 43 demonstrates the sensitivity of NPV to daily mileage. It is observed that BEV will not be profitable for investment until daily mileage exceeds 81 miles. However, as it is running purely on electricity, it returns the highest sensitivity once it breaks even. Breakeven daily mileage of PHEV and HEV is 80 miles very close to that of BEV. Compared with BEV and

PHEV, HEV gives a lower profit since gasoline is still its main energy source. Meanwhile, daily mileage is directly related to transportation GHG emission. According to the study by Felix Kramer[119], CO_2 emission for all the vehicles are estimated shown in Figure 44. It shows that at daily mileage of 50 miles, CO_2 reduction for BEV, PHEV, and HEV are 17.4kg, 15.36kg, and 1.8kg per day. This indicates that by driving a BEV or PHEV, 6.351 and 5.6 tons of CO_2 reduction can be achieved per year. The change of slope for PHEV at 40 miles is because it will switch to CS mode and run on gasoline. With increasing daily mileage, significant difference is observed among all the electric vehicles.

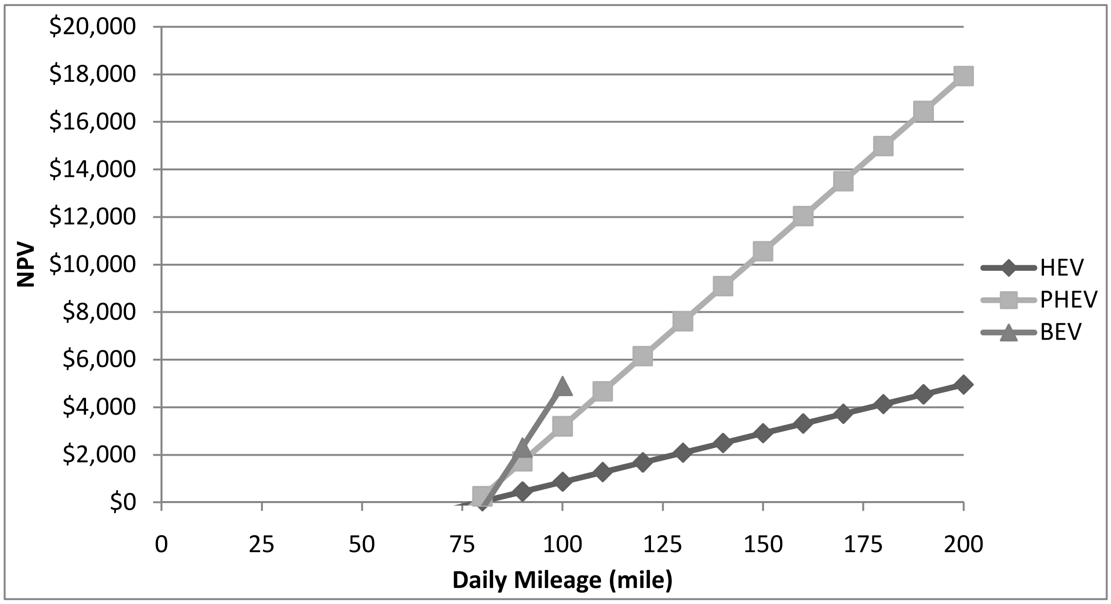


Figure 43 Sensitivity of NPV to Daily Mileage

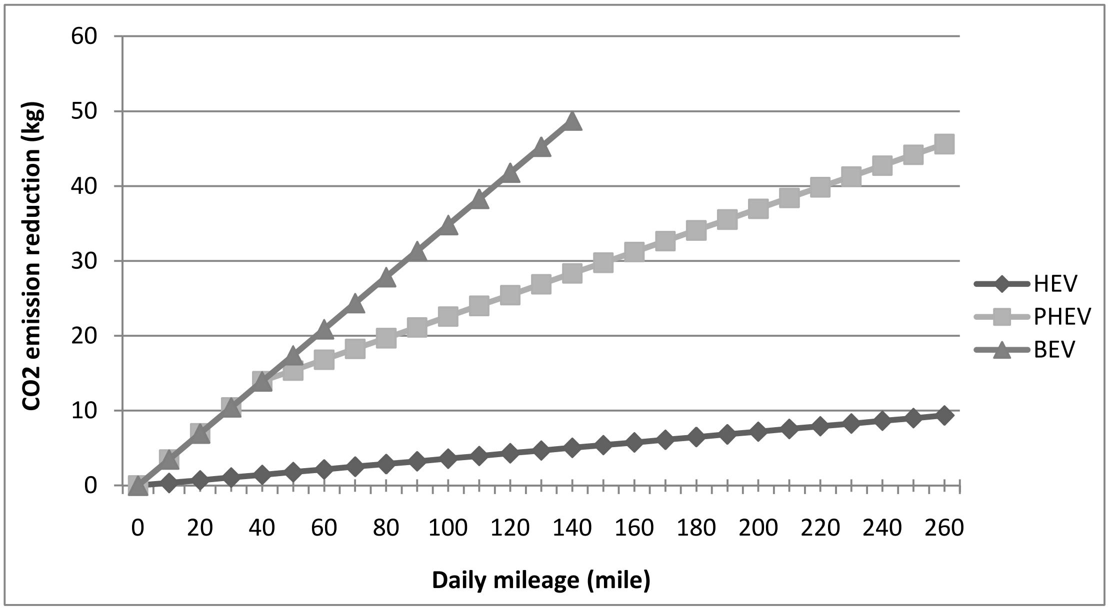


Figure 44 CO_2 Reduction

Gasoline price

Figure 45 shows the break even gasoline prices for HEV, PHEV, and BEV are \$4.5/gallon, \$3.5/gallon, and \$4/gallon. Both PHEV and BEV demonstrate a very competitive profit return with varying daily mileage. Meanwhile, the profit return for HEV is much lower than PHEV and BEV, which means once gasoline price increases, PHEV and BEV will be highly preferred. In fact, US Energy Information Administration has forecasted that the gasoline price will increase to \$2.69/gallon in 2010 due to the boost of crude oil price[121] and further increase in gasoline price could be expected[122]. Meanwhile, government can charge tax on gasoline which will give more incentives for consumers to purchase PHEV and BEV.

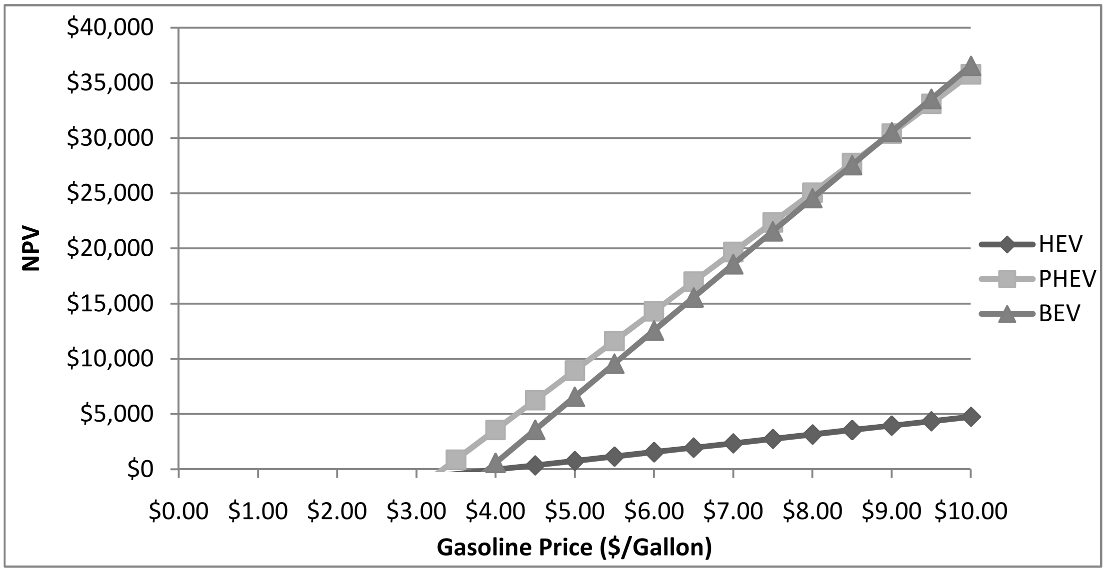


Figure 45 Sensitivity of NPV to Gasoline Price

Government Subsidization

Besides taxing on gasoline, various rebate schemes can able to promote PHEV and BEV. As discussed previously, high premium cost on the battery pack may slow down the adoption rate. Figure 46 shows that with constant HEV subsidization, minimum $4,270 tax credit is needed for purchasing a PHEV. However, for BEV to be profitable, at least $7,726 tax credit should be provided.

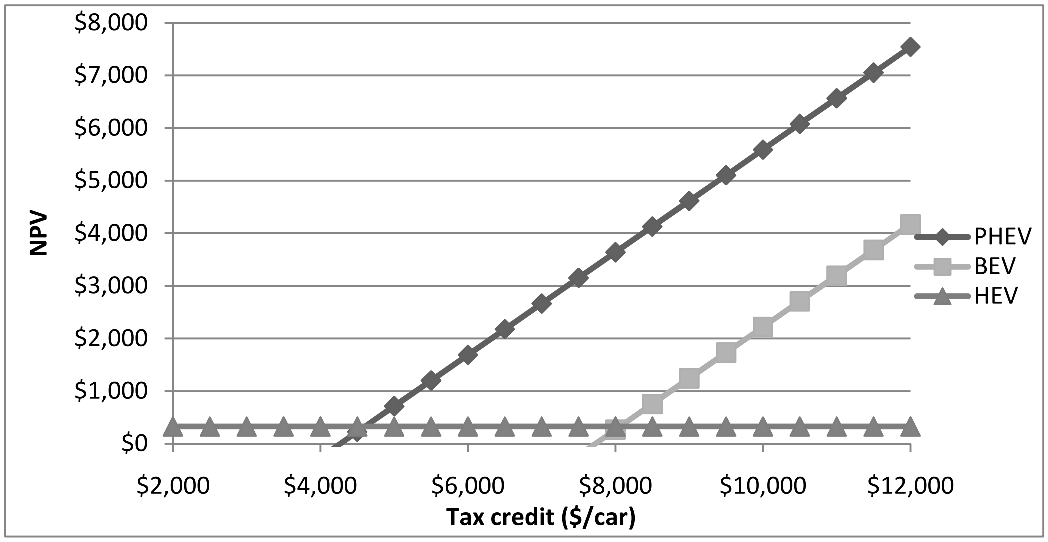


Figure 46 NPV with Various Tax Credit

Chapter 5 Conclusion

Four types of Li-ion battery technologies are assessed and their utilities for plug-in electric vehicles (PHEV) and battery electric vehicles (BEV) are evaluated. The result shows that both lithium manganese oxide ($LiMn_2O_4$) and lithium iron phosphate ($LiFePO_4$) batteries are identified as future energy storage system for automotive application. They exhibit superior safety and improved durability meanwhile with relatively low cost. Currently, the main barrier for their commercialization is cost reduction. Even though lithium cobalt oxide ($LiCoO_2$) battery has high power and energy densities, its thermal instability and expensive cathode have hindered its application in electric vehicles. Current lithium nickel cobalt manganese oxide ($Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$) battery still has a high risk to be used in electric vehicles with long electric driving range such as PHEV and BEV due to its poor durability and unproven safety. Since it has demonstrated excellent power and energy densities, more attentions have been drawn in developing this new battery. If above problems are solved, the cell will provide the same amount of energy by using less cathode materials which may result in a lower cost.

To analyze implementation effectiveness of current Li-ion battery from an end-user's perspective, three factors are employed to compare NPVs of all the electric vehicles. In terms of daily mileage, PHEV and BEV have higher sensitivities than HEV since they require less or no gasoline during operation. However, government will need to subsidize \$4,270 and \$7,726 tax credits for PHEV and BEV to be profitable if they are used as a personal transportation with 50 miles driving per day. On the other hand, if they are used as public transportations such as taxi with longer daily mileages, large profits will be obtained even without any subsidization. In addition, PHEV and BEV give more environmental benefits since GHG reductions of BEV and PHEV are 9.67 and 8.533 times that of HEV. Another factor which influences consumers' decision on choosing electric vehicle is gasoline price. Although it is still affordable to have gasoline cars at current stage, with increasing gasoline price due to crude oil scarce in the long run will urge consumers to drive electric vehicles. To address green house gas emission problem, and reduce oil reliance in the short run, government initiation is the key for fast adoption of PHEV and BEV. By giving subsidizations to electric vehicles or charging tax on gasoline and GHG emission, consumers will have more incentives to choose PHEV and BEV in next few years. At mean time, to reduce upfront cost, battery development which is towards low cost and higher energy density, will be the long term solution for commercialization of electric vehicles.

Chapter 6 Implementation Models in Singapore

Four models are evaluated in the final implementation of electric vehicles based on solar energy in Singapore. All the models have incorporated with inputs from team members' individual thesis reports.

Based on the reviews on Lithium Ion Batteries for Automobiles, Solar Thermal and Solar PV Systems, and Flow Battery technology, the feasibility of implementing EV transportation system based on solar electricity will be investigated. Four different models will be built and evaluated, the Battery Swapping Model, the Private Car Model, the Car Park Charging System based on Stand-along PV system with energy storage, and the Grid-tied PV-EV System model.

Based on H.T. Fu's thesis report, the characteristics of BEV will be used to implement a battery swapping system for the operation of taxis, where the electricity used to power the vehicle is directly drawn from the utility. The economic feasibility and environmental benefits of such a model will be determined.

Similarly, the economical and environmental benefits of PHEV will be evaluated for private transportation in private car model based on the PHEV specifications from H.T. Fu's thesis report.

Car Park Charging System with stand-along solar PV panels and energy storage will evaluate a charging station based on a standalone PV system built on the roof-top of a shopping mall, where PHEVs can be charged with solar electricity stored in the storage system. The economic feasibility and environmental benefits will be evaluated again, followed by respective suggestions to the government in assisting the clean energy policy making.

The Grid-tied PV-EV System is analyzed to evaluate the feasibility of building a large-scale grid-connected PV system which could provide clean electricity to the grid, from which Electrical Vehicles can be charged. The price competitiveness and environmental benefits of solar electricity from such as system will be evaluated, again followed by suggestions to the government in assisting relative the policy making.

6.1 Battery Swapping Model

6.1.1 Background

Battery Electric Vehicle (BEV) is an important player in the green vehicle market. BEV is equipped with a large battery and thus it is able to drive a long distance purely relying on electric power. The optimized battery design is capable for a driving distance of 100 miles per charge. Its average driving speed of 31 miles per hour fits to Singapore traffic condition well, where the average driving speed in Singapore is around 39 miles per hour on expressways and less than 17 miles per hours on artery roads[123]. Moreover, BEV emits no CO2 and produces much lower noise than conventional internal combustion engine vehicle [124].

In addition, a smooth running of BEV systems requires the building of battery swapping stations. The battery swapping stations allows BEV drivers to switch a depleted battery to a fully charged one in a long trip. In a battery swapping station, BEV drivers enters a lane covered with a conveyor. The conveyor will move the car automatically and align the car with battery swapping platform. At this platform, a depleted battery will be taken out from the bottom of the car and replaced with a fully charged one. The depleted battery is then shifted to a store room for charging. After charging, this battery will be available for the next driver. This battery exchange process will be done in a fully automatic way and takes only a few minutes. Since the average daily driving distance of taxis is about 260 miles in Singapore, battery swapping stations must be built to support a smooth running of BEVs[125].

Singapore has excellent infrastructure for building swapping stations, such as robust electric grid, compact urban environment, and advanced IT services[126]. With the support of swapping stations, BEV could travel over long distance and maximally demonstrate its merit of low operating cost. Therefore, it is believed that BEV is one ideal candidate for creating an environmental friendly taxi system in Singapore.

6.1.2 Objective

A proposed BEV taxi model is developed from the perspective of a taxi company. In this model, it is assumed that the taxi company needs to replace 1250 old taxis with new cars. This company has two choices—it can either buy 1250 gasoline cars or 1250 BEVs. A detailed cost model will be built for both choices to assess the economic impact to the taxi company. In particular, for the BEV taxi system, we assume the taxi company will build and operate battery swapping stations.

6.1.3 Economic Analysis

Swapping Stations

Four battery swapping stations will be built to support BEVs as shown in Figure 47. These stations will be built in the west, north, east and downtown area of Singapore, at the locations marked by stars. With these stars as centers, four circles with a radius of 6.25 miles are drawn on the map. This figure shows than almost every corner of Singapore is well covered by these four swapping stations. Considering the overlapped areas among the four circles, it is expected that the average distance between a taxi and a battery swapping station is only about 3 miles. With 3 times swapping per day, and less than one minute swapping speed[127], each swapping station is able to provide swapping service for up to 500 taxis sequentially without any queuing.

Moreover, well established power grid in Singapore is able to support the high power demand from these battery swapping stations. Considering the worse case when all 1250 BEV batteries start to charge simultaneously, it results in the total demand of 61 MW (each BEV battery has charging power of 48.73 kW). This is still a small amount of power compared with the total installed capacity of power plants in Singapore which is about 9775 MW.

All the above facts imply that building the battery swapping station systems for BEV taxis in Singapore is feasible.

Cost Assumptions

The projected cost for constructing a battery swapping station is US$500,000 according to Better Place's estimation [127]. This station is designed to swap batteries, recharge depleted batteries in an entirely automatic process. Three batteries (including the one in use in the car) are prepared for every BEV taxi. They are able to support the taxis to continuously drive for 10 years. Each battery costs about US$18,138 (excluding other taxes). In terms of spare battery pack distributions, east and west stations will prepare for 20% of BEVs, while the downtown station will prepare for 40% of BEVs since it is expected to provide more swapping than the rest. Other assumptions in our model include:

(1) Taxis are sequentially released every day, so that they go back to charging stations roughly sequentially to avoid long time queuing during battery swapping.

(2) The operation and maintenance cost is US$60,000/year for the downtown station and U$50,000/year for the rest stations.

(3) A fully changed BEV battery can store 37 kWh of electrical energy and support the BEV for a 100-mile driving distance. For BEV and its battery specifications please refer to H. Fu's thesis of Assessment of Lithium Ion Batteries for Automobiles.

(4) The average electricity price from year 2005 to year 2009 is calculated to be $0.0931/kWh in Singapore[128] and this price is used in our calculation.

(5) The average taxi daily mileage in Singapore is 258 miles[129].

(6) The average gasoline price from year 2005 to year 2009 is calculated to be $1.86/gallon including tax in Singapore[126] and this price is used in our model.

(7) Another gasoline car, Toyota Crown with fuel efficiency of 21 mpg[130] and upfront cost of $26,058[131], is selected in comparison to BEV during the calculation of their operation costs.

(8) BEVs enjoy Green Vehicle Rebate, which is 40% of vehicle open market value OMV at registration. All vehicles are subjected to registration fee, COE and other fees. Please refer to Chapter 1 for more details about car policies in Singapore.

(9) 7% of GST tax is applied to all commodities in our model.

Figure 47 Battery Swapping Stations in Singapore

Cost Analysis

Based on these assumptions, the operation cost for BEVs is calculated and summarized in Table 24. The cost per mile of BEVs is approximately $0.22.

Swapping Station Infrastructure Cost	$2,000,000.00
BEV Cost	$64,687,500.00
Vehicle cost	$31,250,000.00
Vehicle GST	$2,187,500.00
Green Vehicle Rebate	($12,500,000.00)
Registration fee	$31,250,000.00
COE & Other fees	$12,500,000.00
Number of Battery Pack	$3,750.00
Battery Pack Cost with GST	$73,500,975.00
Total BEV and Battery Cost	$138,188,475.00
Operation Cost	$180,000.00
Electricity cost	$2,392,297.60
Maintenance cost	$250,000.00
Total Variable Cost	$2,822,297.60
Annual interest rate	10%
Infrastructure life time (year)	20
BEV and battery life time (year)	10
Annual Infrastructure Amortization	$234,919.25
Annual BEV & Battery Amortization	$22,489,537.93
Annual Fixed Cost	$22,724,457.18
Annual Variable Cost	$2,822,297.60
Total Annual Cost	$25,546,754.78
Total Annual Cost per Car	$20,437.40
Cost per Mile for a BEV	$0.217

Table 24 Cost of Battery Swapping Model for BEVs

The cost breakdown of BEV system is shown in Figure 48. It is observed that the major cost is from BEV and battery packs. The infrastructure is only about 1% of the total cost. The second largest cost is from electricity. This indicates that a higher penetration rate of BEVs into the taxi markets does not necessarily reduce its cost per mile, because the cost for BEVs is mainly from vehicles, batteries and electricity.

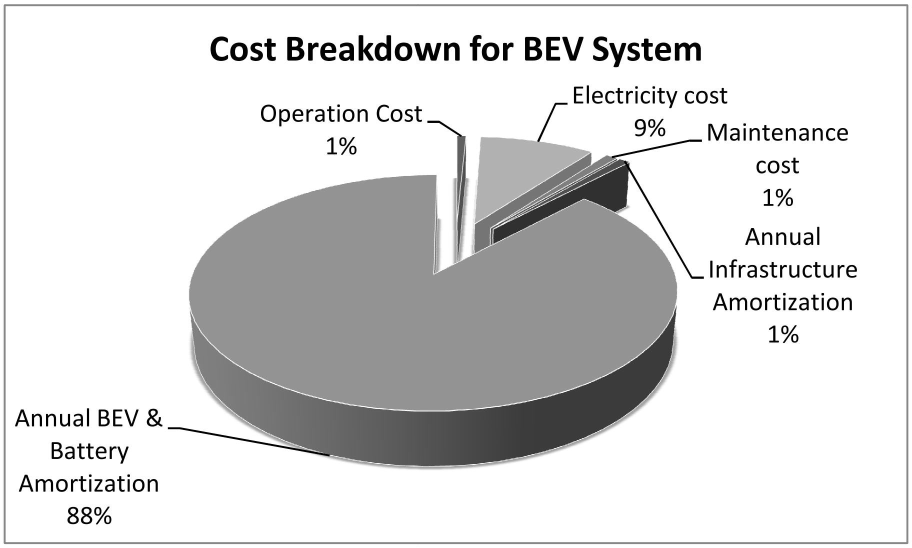


Figure 48 Cost Breakdown of BEV System

Similarly, the implementation cost of $0.199/mile for gasoline taxis are calculated shown in Table 25.

Toyota Crown Taxi	$63,940.06
Vehicle cost	$26,058.00
Vehicle GST	$1,824.06
Registration fee	$26,058.00
COE & other fees	$10,000.00
Toyota Crown Amortization	$10,405.95
Fuel Efficiency (mpg)	21
Gasoline Price ($/gallon)	$1.860
Daily gasoline consumption (gallon)	$22.85
Daily Operation Cost	$8,340.77
Annual Operation Cost	$8,340.77
Annual gasoline consumption (gallon)	
Total Annual Cost for Gasoline Car	$18,746.72
Cost per Mile for Gasoline Car	$0.199

Table 25 Cost of Gasoline Cars

From above calculations, it can be seen that BEV taxis are not cost competitive compared to gasoline taxis. The cost per mile for BEV is 9% more expensive than that of gasoline taxis.

Further sensitivity analysis of the system cost to gasoline price is provided to obtain the breakeven gasoline price for BEV taxi system.

First, the relationship between gasoline and electricity prices in Singapore is analyzed. The monthly average price of both gasoline and electricity (wholesale electricity price) in Singapore from 2005 to 2009 are calculated[132, 133]. The electricity price is converted into U.S dollar at exchange rate of US$1=S$1.44. As shown in Figure 49, it is found that electricity retail price is very close to the gasoline price. Therefore, a linear relationship between these two prices is assumed.

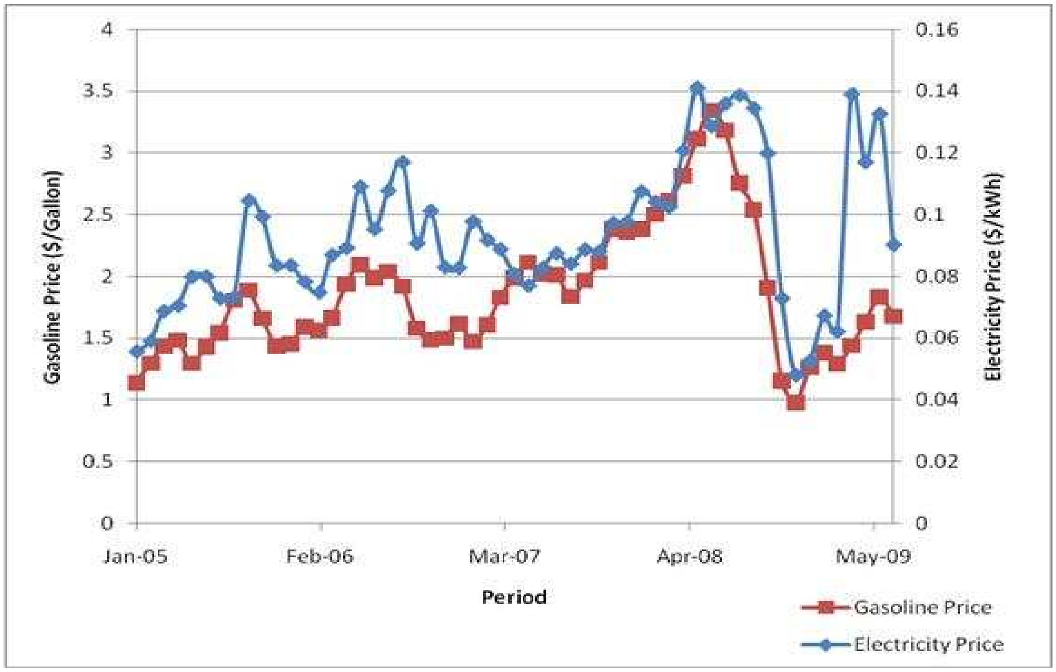


Figure 49 Monthly Average Prices of Gasoline and Electricity in Singapore

The cost per mile for both BEV taxis and gasoline taxis are calculated and plotted in Figure 50. With increasing gasoline price, cost per mile of gasoline taxi ramped up rapidly. The cost per mile of BEV taxis is also increasing with a much lower rate since electricity cost is insignificant in terms of total system cost. The breakeven price for BEVs and gasoline cars occurs at gasoline price of about $2.4/gallon.

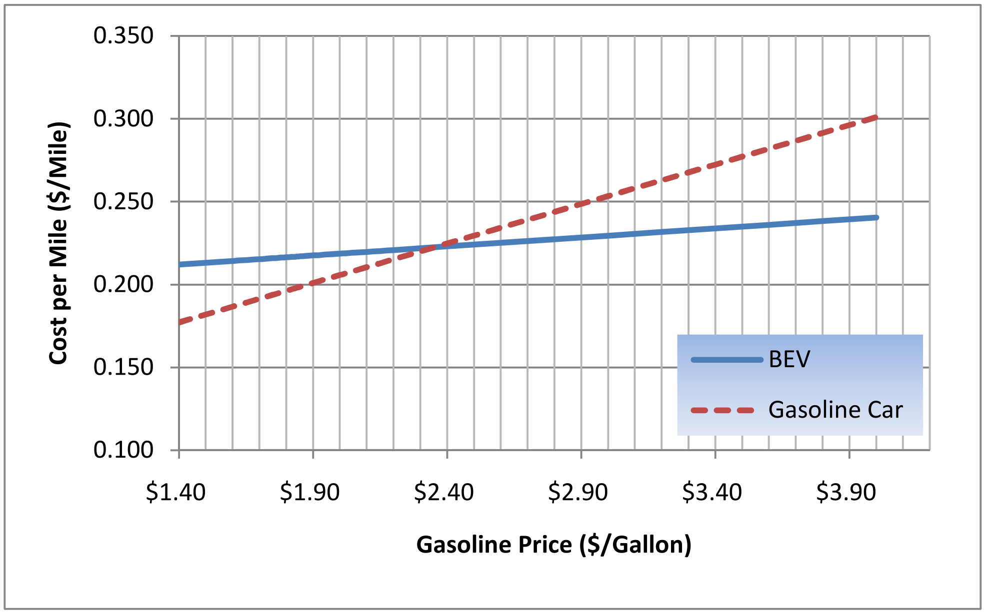


Figure 50 Cost per Miles for Gasoline Cars vs. Gasoline Price

6.1.4 Environmental Analysis

From environmental perspectives, BEV taxis are highly preferred for less CO_2 emission. In order to quantify its environmental benefits, CO_2 is priced in order to find the breakeven price for BEV taxi system.

The main source of CO_2 emission for BEV taxi is from electricity generation. Amount of CO_2 emitted during electricity generation can be calculated based on the following assumptions:

(1) Average transmission loss from power station in Singapore is estimated to be 1.5%[134].

(2) Average CO_2 emission during power generation is 434g/kWh in Singapore[135].

(3) Estimated CO_2 emission for gasoline taxi is 371.2g/mile based on the data given by Felix Kramer[119].

Table 26 shows that by operating BEV taxi, 0.27kg/mile of CO_2 reduction can be achieved compared with its gasoline counterpart. The total CO_2 reduction for a single BEV in one year (assuming daily driving distance of 258 miles) can be as high as about 25 tons. This would mean a total of nearly 31.3 kilo tons of CO_2 reduction yearly. Moreover, if this electricity is from renewable energy, the CO_2 reduction can go up to 0.371 kg/mile or an annual saving in CO_2 reduction of nearly 35 tons per car.

	CO2 emission (kg/mile)
BEV taxi	0.09548
Gasoline taxi	0.3712235
BEV taxi CO2 reduction	0.2757435

Table 26 CO2 emission of BEV and Gasoline Taxis

In order to reduce CO_2 emission and promote BEV taxi system in Singapore, incentives must be given by Singapore government. Based on the previous cost analysis, a price of \$70.21/ton of CO_2 emission is needed so as to make BEV taxi at the same cost level of gasoline taxis, at present gasoline and electricity prices (\$0.093/kWh for electricity and \$1.86/gallon for gasoline). In comparison, according to the CO_2 price established by European Union's Emissions Trading Scheme (EU ETS), current CO_2 is charged at \$21.3/ton[136], and it will increase further to \$56.86 by 2016 in Europe. Therefore, from increasing trend of gasoline price and CO_2 trading price, it is highly likely that BEV taxis will be running in Singapore in near future.

6.2 Private Car Model

6.2.1 Background

According to Land Transport Authority (Singapore), the average daily mileage of private cars is 35.4 miles[129]. As shown in H.T. Fu's model, under current technical standard, Plug-in Hybrid Electric Vehicle (PHEV) has a driving distance of 40 miles by operating in electric mode. This is enough to cover the entire daily mileage of a private car user. While the operation cost and CO_2 emission for PHEV and BEV are quite similar, PHEV has a much less upfront cost compared to BEV. Therefore, PHEV is chosen to target at private car market in this Private Car Model.

6.2.2 Assumptions

By applying the same topology as in BEV battery swapping model, economic and environmental impacts of PHEVs are assessed based on following assumptions:

(1) Average daily mileage of a private car is 35.4 miles.
(2) Gasoline and electricity prices are \$1.83/gallon and \$0.0932/kWh respectively.
(3) PHEVs enjoy Green Vehicle Rebate, which is 40% of the vehicle's open market value (OMV) at registration.
(4) All vehicles are subjected to registration fee, COE and other fees.
(5) 7% of GST tax is applied to commodities.
(6) A fully charged PHEV can drive for 40 miles in electric mode. After that, it operates as a hybrid electric vehicle (HEC) with a fuel efficiency of 50 mpg.
(7) A gasoline car with a fuel efficiency of 26.4 mpg is used for comparison.

6.3.3 Cost Model

The result is summarized in Table 27. As shown in this table, although PHEV has a higher upfront cost than gasoline car, drivers could making savings from its lower operating cost. Nevertheless, a negative net present value in Table 27 indicates that this saving is not large enough to offset the high upfront cost of a PHEV. As a result, at current electricity and gasoline prices, it is not cost effective for a consumer to purchase a PHEV.

PHEV cost	$73,972.69
PHEV OMV price	$38,307.00
PHEV GST	$2,681.49
Green vehicle rebate	($15,322.80)
Registration fee	$38,307.00
COE & other fees	$10,000.00
Gasoline car cost	$56,212.75
Gasoline car OMV price	$22,325.00
Gasoline car GST	$1,562.75
Registration fee	$22,325.00
COE & other fees	$10,000.00
PHEV initial investment	$17,759.94
PHEV operation cost	$0.72
Gasoline operation cost	$2.49
Daily PMT(saving)	$1.77
Annual PMT(saving)	$644.62
Annual interest and inflation rate	2.5%
Net present value	($11,822.59)
PHEV CO2 emission (kg/day)	3.87736
Gasoline car CO2 emission (kg/day)	12.3192
PHEV CO2 reduction (kg/day)	8.44184

Table 27 Implementation Cost of PHEV vs. Gasoline Car

The sensitivity of NPV to gasoline price is analyzed. The same relationship between gasoline and electricity price as in Battery Swapping Model is used. Figure 51 shows the change of NPV as gasoline price increases. It is observed that PHEV will not be profitable unless the gasoline price goes to as high as about \$5.4/gallon. Based on the historic trend of gasoline price in Singapore, this price is not likely to occur in the short run.

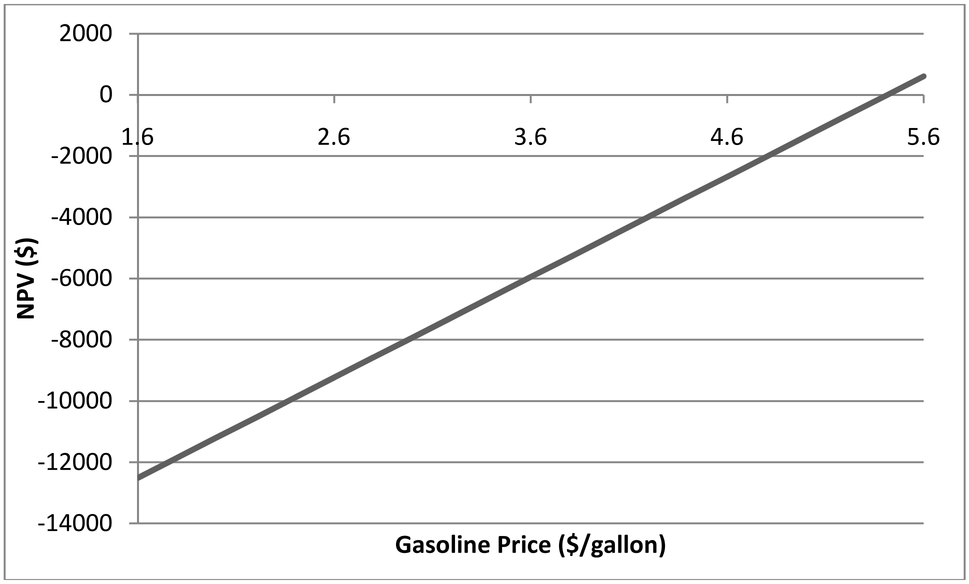


Figure 51 NPV vs. Gasoline Price

From environmental perspectives, operating a PHEV can achieve 8.442 kg of CO_2 reduction every day than running a gasoline car. In order to make PHEV as cost competitive as a gasoline car, the charge of \$\$355/ton on CO2 emission is required to bridge this cost gap. This price is as high as 17.5 times of the current CO_2 trading price (\$21.6/ton) in the European Union. Therefore, at this moment PHEV is not likely to be adopted as private cars.

As the driving distance becomes longer, PHEV's merit of low operation cost becomes more significant. Sensitivity of CO_2 breakeven price with varying daily mileage is shown in Figure 52. This figure suggests that PHEV is probably a good choice for users of higher daily mileage, such as postman.

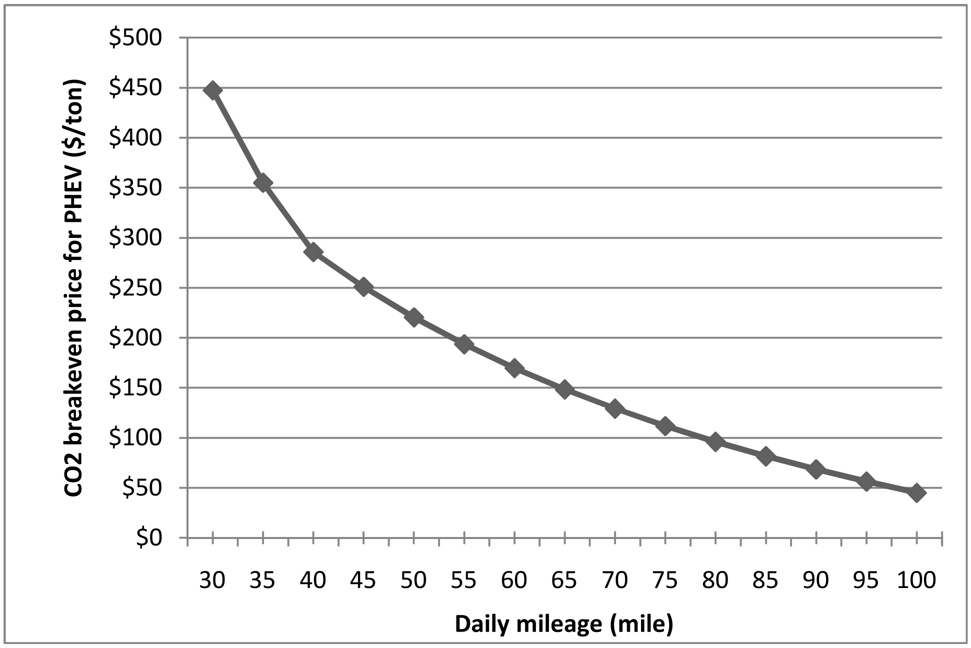


Figure 52 CO2 Breakeven Price with Varying Daily Mileage

6.3 Car Park Charging System Model

6.3.1 Background

In order to help expedite the penetration of electric vehicles (EV) into the private car market in Singapore, supporting infrastructures for EV should be built at the frequently and easily accessible areas with dense population of cars. One of the most important infrastructures is the charging system.

Singapore has limited land, so its city planning does not allow much space for private parking. Aggregated public cars parks are commonly seen around the island, at both residential and commercial areas. The residential areas in Singapore mainly comprise of tall flats, and separate multi-storey buildings are usually built for car parking for the residents in the region; it is also very common to see aggregated large-scale shopping complexes in Singapore, and the parking spaces are usually located within the same building. Therefore, providing charging spots at those parking areas can help alleviate EV users' worries of running out of "fuel", while they are resting at home or shopping with families for the weekends.

In order to make EVs even "greener", solar energy technology should be leveraged for the greater benefit to the environment. This is because solar energy is the only viable clean energy resource for electricity generation in Singapore, as being discussed in Report 1. Solar thermal technology and solar PV technology are separately evaluated by Liu and Sun in their respective thesis. According to Liu, solar thermal technology is not suitable for electricity generation in Singapore due to its low efficiency in a highly diffusive radiation environment, like Singapore[1].

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[1] According to Liu, to make it economically sound, solar thermal power plant requires a minimum daily direct normal isolation of 6 kWh/m2. However, due to more than 40% of diffusive radiation, the daily DNI in Singapore is less than 3 kWh/m2. Moreover, solar thermal power plant requires a vast area for solar field. This further prevents it from entering the Singapore market, when the density of population is ranked number 2 in the world.

Therefore, solar PV technology is chosen for evaluation in this car park model.

Furthermore, to fully capitalize on the solar energy available only during sunny daytime, energy storage system should be implemented together with the PV panels to make the solar energy even available for charging at night or during cloudy days. Moreover, energy storage system can eliminate the intermittent nature of electricity generation from solar PV.

6.3.2 Objectives

The ultimate aim of this Car Park Charging System (CPCS) model is to evaluate the profitability of building a Standalone Solar Electricity Generation System with Energy Storage (SSEGS-ES).

The final cost of electricity in $/kWh generated from the SSEGS-ES system (P1) will be compared with the current utility electricity price (P2) and the equivalent electricity price for the conventional combustion engine vehicles (P3). Based on the comparison, EV users' acceptance level and the future market of CPCS can be analysed. Correspondingly, possible policies and acts can be proposed to the government to incentivise such a system.

6.3.3 Assumption

There are a few important assumptions for building such an implementation model:

(1) The solar PV technology is based on the one evaluated in Sun's thesis. The capital cost of building such a solar PV panel is also obtained from the cost model in that thesis. The energy storage system makes use of the vanadium redox flow battery system (VRB) evaluated in Chen's thesis, likewise for its capital cost modeling.

(2) The specifications of EV batteries and charging parameters are obtained from Fu's thesis on EV battery evaluation. Based on his thesis, Plug-in Hybrid Electric Vehicle (PHEV) is believed to be the most suitable model for private car users in Singapore, because of its

relatively low overall cost in $/mile and sufficient driving range for private car users in Singapore. Herein, PHEV is used together with SSEGS-ES for the implementation model.

(3) The CPCS is assumed to be continuously operational for twenty years from its commissioning.

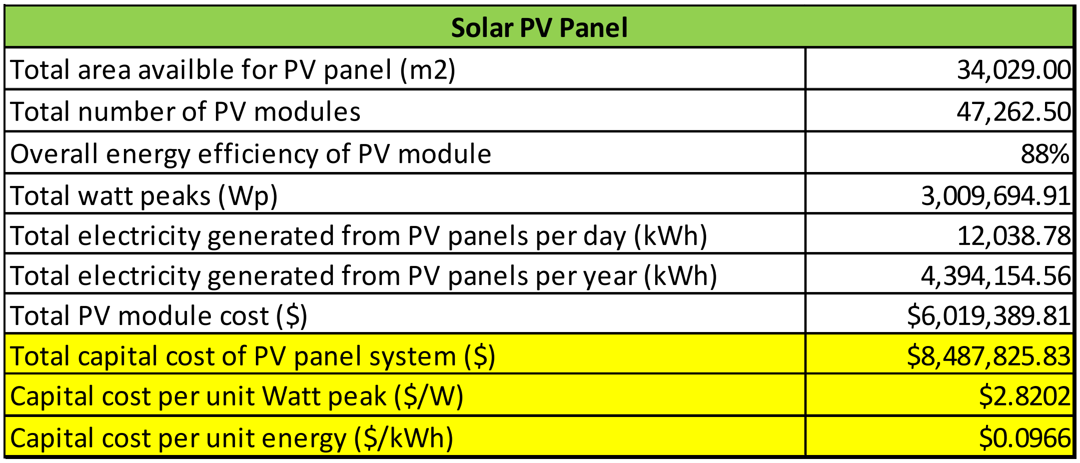
(4) An initial capital investment is used to build the entire CPCS, including the solar PV panels, VRB storage system and the auxiliary components. The balance-of-plant is included in the individual systems, and the final operation and maintenance (O&M) cost for the entire CPCS is incorporated into the initial capital investment. This lump-sum capital investment is taken from a bank loan with annual borrowing rate of 5%. The loan is paid back with equal annual installment for the next twenty years.

(5) The installed CPCSs is purchased by and owned the operators of the car parks, who can be the owners of shopping complexes and the neighborhood communities of the residential areas. They will charge the EV users for charging their vehicles during parking. This constitutes income for the CPCS owners who can use it to repay the bank loan for the next twenty years. The interest rate is assumed to be constant at 1% for the next twenty years, and the inflation rate is assumed to be zero in Singapore for this period.

6.3.4 Cost Model

Car park

The car park used in this model is the one used in one of the largest shopping complexes in south-western Singapore, the IMM shopping mall[137], respectively. IMM is purposely chosen for this model, because it is located between the downtown area and the rural suburbs, its accessibility and traffic amount can reasonably approximate the average standards in Singapore. The roof-top area of IMM building is estimated to be about 37,810m^2, and there are about 1,300 car park lots available inside [138]. This is another reason for choosing IMM for the SSEGS-ES implementation, and more details will be presented in later sections. Solar PV panelsBased on Sun's model of solar PV panels, it is assumed that 90% of the roof-top areas can be covered with PV panels, which is equivalently 37810×90%=34,029m^2. Assuming 90% of the roof-top areas are covered with solar PV panels, so that the total number of PV modules needed is about 51,250, each taking up an area of 0.72m^2. The solar PV panels are made from Cd-Te module from First Solar®. The important parameters and final capital cost of the solar PV panels are shown in Table 28. The total capital cost for the entire solar PV panels is about $8,497,825.83. The breakdown of this total amount is shown in Figure 53. It can be seen the PV module cost amounts to more than 70% of the total cost.



Solar PV Panel	
Total area availble for PV panel (m2)	34,029.00
Total number of PV modules	47,262.50
Overall energy efficiency of PV module	88%
Total watt peaks (Wp)	3,009,694.91
Total electricity generated from PV panels per day (kWh)	12,038.78
Total electricity generated from PV panels per year (kWh)	4,394,154.56
Total PV module cost ($)	$6,019,389.81
Total capital cost of PV panel system ($)	$8,487,825.83
Capital cost per unit Watt peak ($/W)	$2.8202
Capital cost per unit energy ($/kWh)	$0.0966

Table 28 Important parameters and final capital costs of the solar PV panels installed for car park in the IMM shopping hall

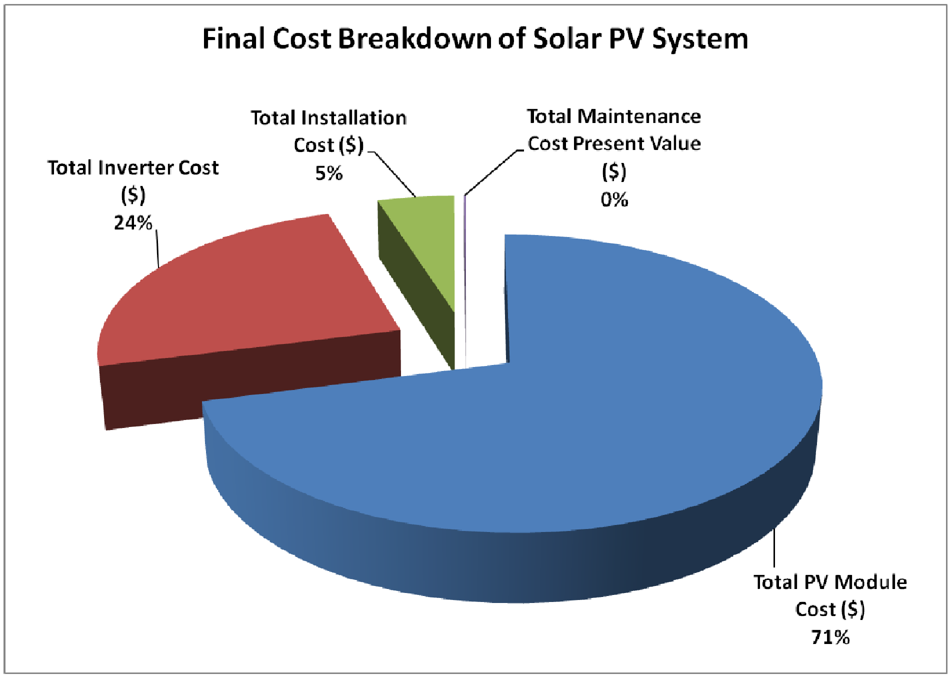
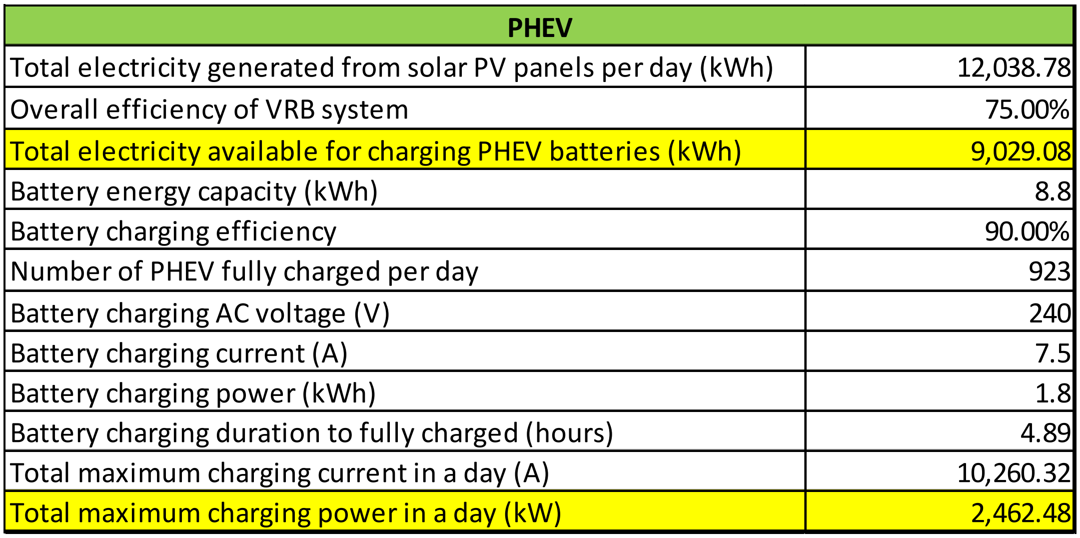


Figure 53 Final Cost Breakdown of the Entire Solar PC System

PHEV specifications

The PHEVs are driven by advanced Li-ion batteries which can be plugged into any normal power socket that provided 240V AC power supply. Based on Fu's model of Li-ion batteries and reference [139], the charging characteristics PHEV batteries are shown in Table 29. The charging efficiency is assumed to be 90%; based on Chen's model of VRB system, the overall energy efficiency (input/output) is about 75%. The total electricity available for charging PHEV batteries is therefore calculated to be about 9,029kWh per day, and the number of PHEV batteries that can be fully charged is about 923 per day. This is smaller than the total parking lots available (about 1,300). Assuming that all the 923 PHEVs are plugged-in and charged from the VRB system at the same time, the maximum power capacity requirement for the VRB system hence is about 2.462MW.



PHEV	
Total electricity generated from solar PV panels per day (kWh)	12,038.78
Overall efficiency of VRB system	75.00%
Total electricity available for charging PHEV batteries (kWh)	9,029.08
Battery energy capacity (kWh)	8.8
Battery charging efficiency	90.00%
Number of PHEV fully charged per day	923
Battery charging AC voltage (V)	240
Battery charging current (A)	7.5
Battery charging power (kWh)	1.8
Battery charging duration to fully charged (hours)	4.89
Total maximum charging current in a day (A)	10,260.32
Total maximum charging power in a day (kW)	2,462.48

Table 29 Important parameters for PHEV batteries

Capital cost of VRB storage system

The VRB system will be constructed in the proximity of the IMM building. A computerised control system will be installed to dynamically control the charging and discharging dynamically of VRB system. The electricity will be generated with intermittence from the solar PV panels at sunny daytime, and then it can be supplied to the charging spots throughout the car park inside the IMM building at anytime of the day.

From the previous section on PHEV specifications, the total maximum charging power required from the VRB system is about 2.462MW. A 100kW safety margin is added to the maximum power output of VRB system, resulting in 2.562MW. The discharge duration is estimated to be 4 hours, resulting in a total energy capacity of 10,240kWh of the VRB system which is larger than the required total electricity for charging 923 PHEVs fully per day, 9,029kWh (highlighted in yellow in Table 29). Hence, the final purchase price of the entire VRB system is $3,213.098.06 for a 2.562MW VRB system with discharge duration of 4 hours. Based on Chen’s model, the final capital cost per cycle is about $0.0836/kWh. A summary is shown in Table 30.

VRB Storage System	
Output Power Capacity (kW)	2,562
Discharge Duration (hours)	4
Total energy capacity (kWh)	10,248.00
Capital cost per unit power ($/kW)	$548.50
Capital cost per unit energy ($/kWh)	$134.65
Fixed cost ($)	$135,800.00
Total capital cost ($)	$2,920,998.23
Total purchase price ($)	$3,213,098.06
Capital Cost per Cycle ($/kWh)	$0.0836

Table 30 Important specifications and final purchase price of the VRB storage system

Figure 54 shows the breakdown of final cost of the entire VRB system. Due to the large power and energy capacity of the power plant, the fixed cost component only constitutes about 2% of the total cost, whereas the cell stacks and the vanadium electrolyte amounts to more than 55%.

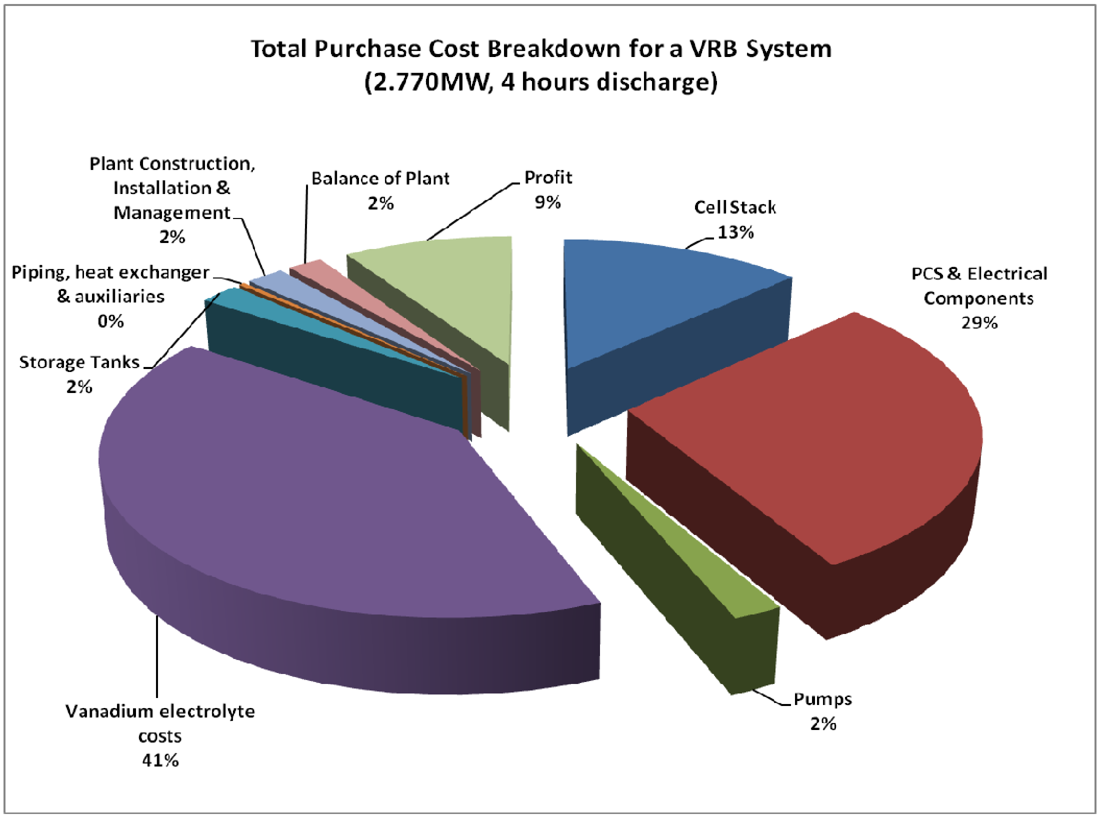


Figure 54 Final cost breakdown for VRB system with 2,770kW with 4 hours discharge duration

O&M cost of the CPCS

Since in both Sun's cost model of solar PV panels and Chen's cost model of VRB system, the O&M costs are included in the final capital costs, there is no separate O&M cost associated with the CPCS system. Based on the previous discussion, the total initial capital cost amounts to $11,700,923.89 in total. Figure 55 shows the final cost breakdown: VRB system costs about 27% and the solar PV system takes up the remaining 73%.

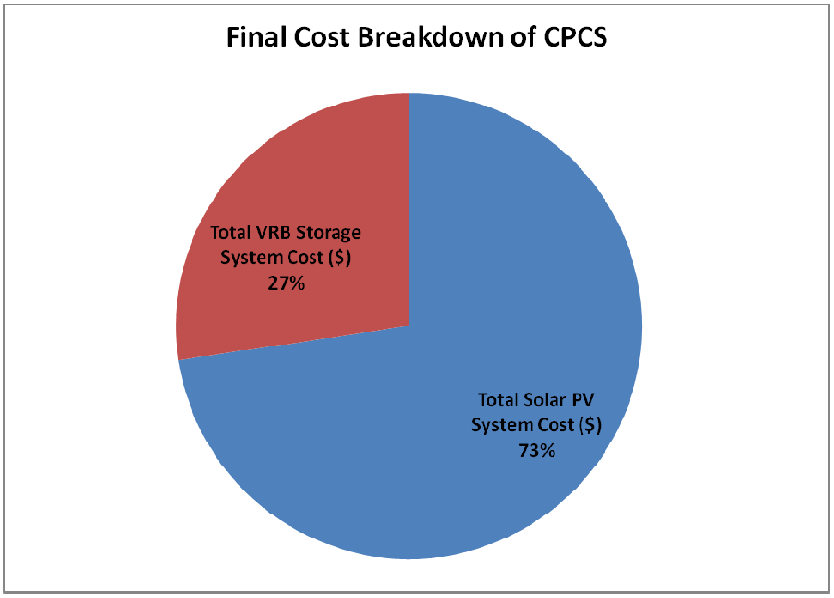
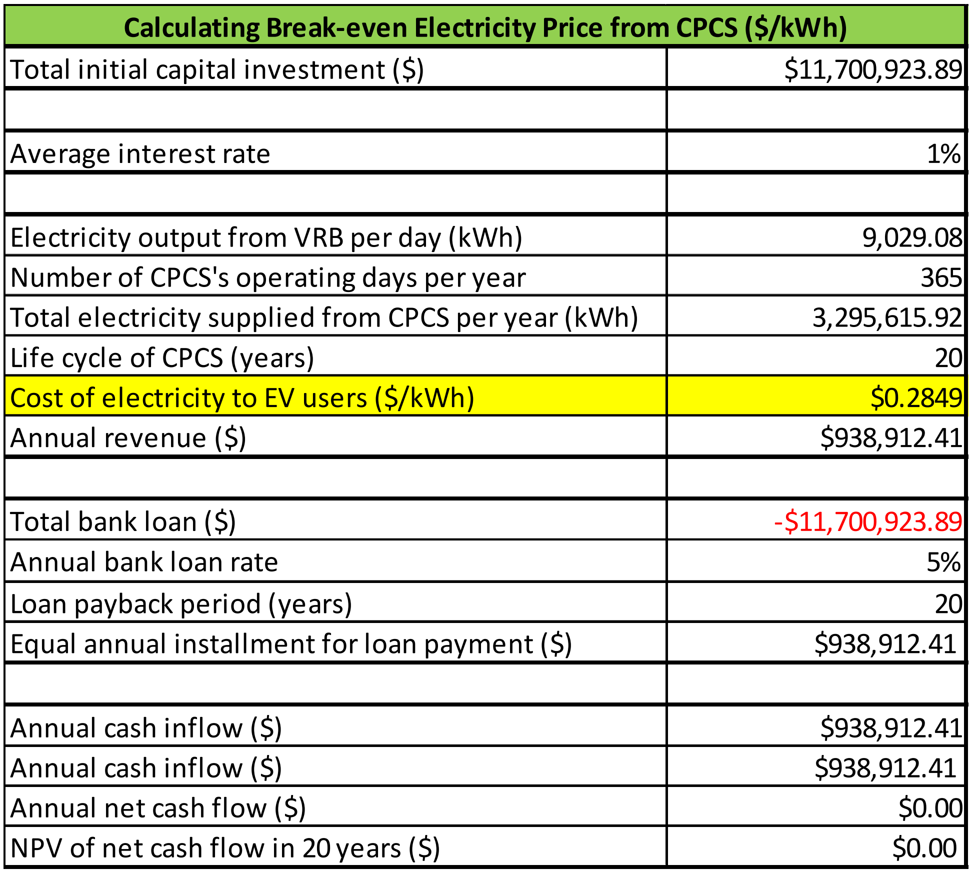


Figure 55 Final cost breakdown of the CPCS system installed in IMM building

It is assumed that this amount is loaned from a local bank with borrowing rate of 5%, with payback period of 20 years of equal annual payment. Hence, the annual instalment is $938,912.41. Electricity from the CPCS is sold the EV user. Once they plug-in their PHEV onto the wall-plug in the car park, the power meter installed beside the charging spot will start to calculate the total charging cost. The cost of electricity for the next twenty years is assumed to be constant. In order to find the break-even electricity price (denoted as P1), the annual income from electricity sale must be equal to the annual loan payment. This is calculated to be $0.2849/kWh. Table 31 shows the important parameters for this calculation.



Calculating Break-even Electricity Price from CPCS ($/kWh)	
Total initial capital investment ($)	$11,700,923.89
Average interest rate	1%
Electricity output from VRB per day (kWh)	9,029.08
Number of CPCS's operating days per year	365
Total electricity supplied from CPCS per year (kWh)	3,295,615.92
Life cycle of CPCS (years)	20
Cost of electricity to EV users ($/kWh)	$0.2849
Annual revenue ($)	$938,912.41
Total bank loan ($)	-$11,700,923.89
Annual bank loan rate	5%
Loan payback period (years)	20
Equal annual installment for loan payment ($)	$938,912.41
Annual cash inflow ($)	$938,912.41
Annual cash inflow ($)	$938,912.41
Annual net cash flow ($)	$0.00
NPV of net cash flow in 20 years ($)	$0.00

Table 31 Calculation of the break-even electricity price for the next twenty years

Therefore, the final break-even electricity retail price from the CPCS at IMM building should be P1 = $0.2849/kWh.

6.3.5 Model Analysis

Utility electricity price, P2

The yearly average electricity price from 2005 to 2009 is shown in Table 32. The average electricity price during this period is $0.0932/kWh, and this is taken as a reference of the expected average electricity retail price in the next twenty years. Hence, P2 = $0.0932/kWh. This is about third (~32.7%) of P1.

Year	Electricity Price ($/kWh)
2005	$0.0775
2006	$0.0929
2007	$0.0884
2008	$0.1128
2009	$0.0943
Average	$0.0932

Table 32 The yearly average electricity price in Singapore from 2005 to 2009

Sensitivity Analysis – Car Park Roof-top Area

Figure 56 shows that P1 decreases with the car park roof-top area available for PV installation. It approaches towards about $0.275/kWh when the roof-top area goes to very large. This "asymptotic" value is about 3 times of the average utility electricity price, P2 (shown as the red line in Figure 56), and about 2 times of the highest historical utility electricity price in the past five year. The vertical dotted line represents the case of CPCS built on IMM building.

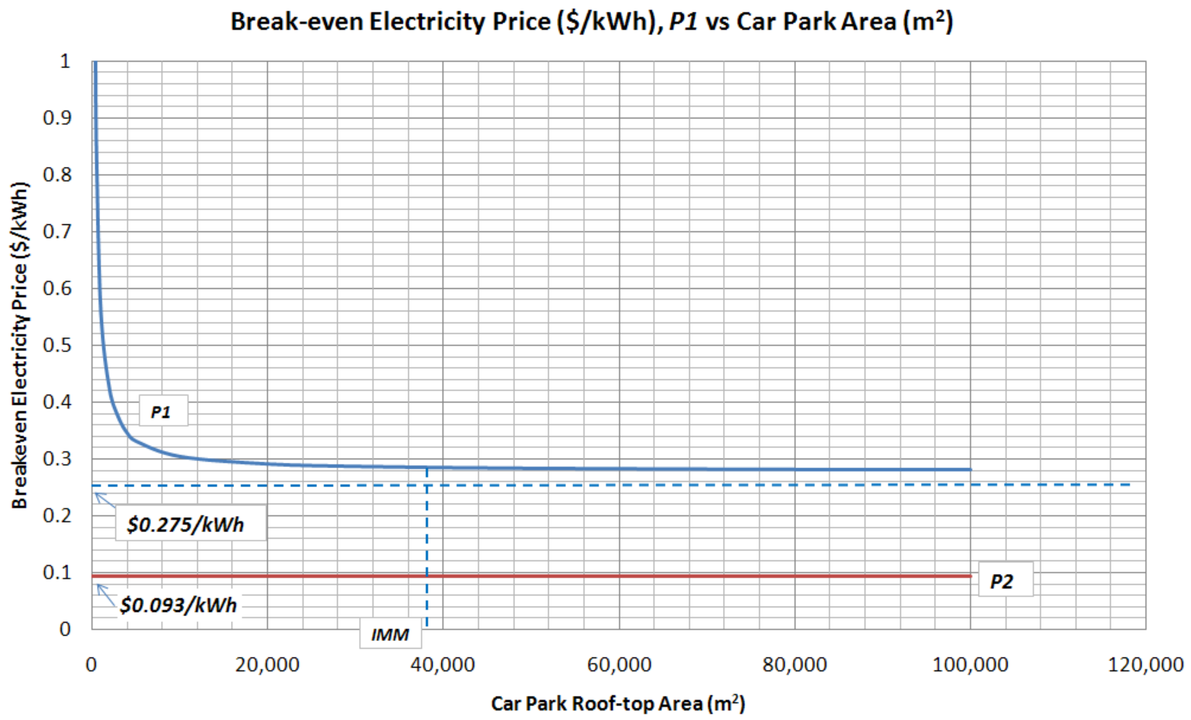


Figure 56 Variation of break-even electricity price from CPCS (P1, $/kWh) against car park area (m^2) and utility electricity price (P2, $/kWh)

The initial quick decrease in P1 with increasing car park roof-top area is due to the relatively large portion of capital investment in building CPCS, even when the amount of electricity generated from the PV panels is very limited. This can be seen from Figure 57 which shows comparison of increasing rates of total cost of CPCS and annual electricity generation capacity, with respect to the roof-top area, as well as the increasing rates of total cost of VRB system and total cost of solar PV system. When the roof-top area is below 100m^2, the annual electricity generation solar panel is only about 40kWh, but the total capital cost of CPCS is already above $300,000. When the roof-top area gets larger, the incremental electricity generated exceeds the incremental capital cost of CPCS, so the final break-even electricity price comes down due to economy of scale. This is shown in Figure 57 in which the electricity generation curve (purple) is much steeper than the total CPCS cost curve (green). Furthermore, it shows that when the roof-top area is small and the generation capacity is small, the total capital cost of VRB storage system is higher than that of solar PV system; when the roof-top area goes above 2,000 m^2, the total cost of solar PV panels overtakes that of VRB system. This is mainly due to the decreasing capital cost per cycle with increasing energy capacity of VRB system discussed in Chen’s thesis.

Therefore, a conclusion that can be made is that car parks with large roof-top area available for installing more PV modules will be more economically attractive for building CPCS. In fact, IMM mall is one of the handful large shopping complexes in Singapore with large roof-top area. This is also another reason for choosing IMM for the initial stage of modeling.

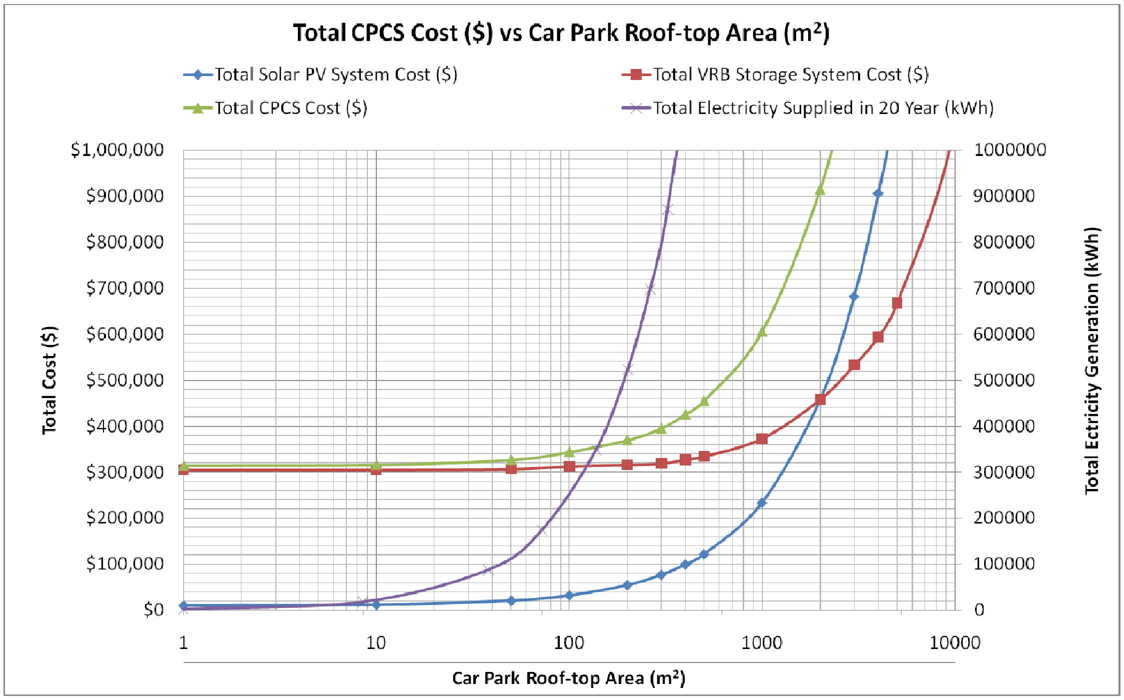
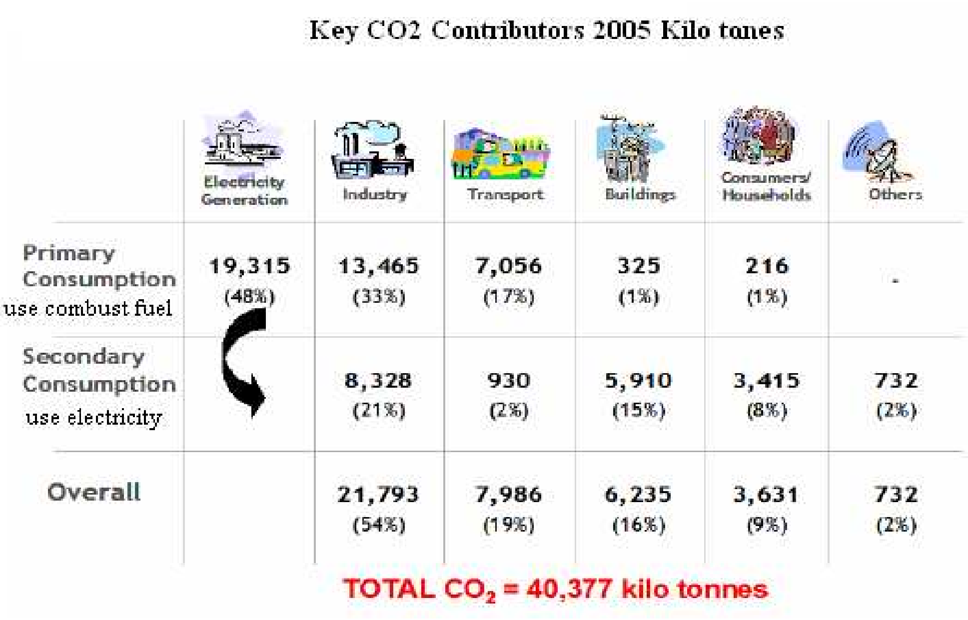


Figure 57 Total cost of CPCS, total VRB system cost, total solar PV system cost and annual electricity supplied by CPCS vs car park roof-top area (ranging from 1m^2 to 10,000m^2, log scale)

Carbon Dioxide (CO2) Emission Reduction

Apparently, the price of electricity generated from the CPCS system modelled above is too expensive to be accepted by ordinary PHEV users, they may prefer to charge their vehicles from the household wall-plug with only one third of the cost of using CPCS. However, the electricity generated from CPCS is totally carbon-emission free, and it is much “cleaner & greener” than the utility electricity generated from the ordinary power plants. Most of power plants in Singapore use natural gas to generate electricity, and power generation sector alone contribute the largest portion of total CO_2 emission in Singapore. This is shown in Figure 58[140].



Key CO2 Contributors 2005 Kilo tones

	Electricity Generation	Industry	Transport	Buildings	Consumers/ Households	Others
Primary Consumption use combust fuel	19,315 (48%)	13,465 (33%)	7,056 (17%)	325 (1%)	216 (1%)	-
Secondary Consumption use electricity		8,328 (21%)	930 (2%)	5,910 (15%)	3,415 (8%)	732 (2%)
Overall		21,793 (54%)	7,986 (19%)	6,235 (16%)	3,631 (9%)	732 (2%)

TOTAL CO_2 = 40,377 kilo tonnes

Figure 58 CO_2 Emission by Sectors in Singapore in 2005.

In order to make the clean electricity generated from standalone solar electricity generation system with energy storage (SSEGS-ES) at least equally competitive with the gas-generated electricity, government’s restriction on CO_2 emission is essential. This can be done in the form of carbon credit trading system seen in some European countries. In this system, carbon is being sought and bought just like other commodities in the market. The party who can reduce their CO2 emission will have more carbon credits to sell to those who need to emit more CO_2 than required by the government. In this way, PHEV users who use clean electricity to driven their vehicles will earn carbon credits, equivalently to reducing operating cost of PHEV. Therefore, in this implementation model of EV in Singapore, it is assumed that Singapore government has joined the global carbon trading system, and allows its citizen to participate in the trading activities just like trading stocks. A carbon trading price in $/Ton needs to be determined in order to let solar-generated electricity and gas-generated electricity be equally attractive to EV users. The carbon intensity from the two largest power generation companies in Singapore, Tuas Power[141] and Senoko Power[142] are used to estimate the mass of CO_2 emission when 1kWh electricity is generated from natural gas. Averaging the Senoko's carbon intensity in 2005 (450g/kWh) and Tuas' carbon intensity in 2006 (418g/kWh), the approximate carbon intensity for gas-generated electricity in Singapore is about 434g/kWh. It is further assumed that the power transmission efficiency from power plant to end EV users is 98%, so the actual carbon intensity per kWh electricity charged into EV is about 442.86g/kWh.

Based on the previous modelling on IMM building, the price of electricity from CPCS is \$0.2849/kWh, and the utility (gas-generated) electricity price is \$0.0932/kWh, so the price difference is \$0.1917/kWh. In order to bridge this price gap, the CO2 emission per kWh of gas-generated electricity needs to be charged. The unit carbon price is therefore:

$$\frac{\$0.1917/\mathrm{kWh}}{442.86\mathrm{g}/\mathrm{kWh}} \approx \$0.43287/\mathrm{kg} = \$432.87/\mathrm{ton}$$

Hence, in order to let solar-generate electricity's price and gas-generated electricity's price equal, the break-even price of CO2 should be \$432.87/ton.

"Best case" analysis

From the previous section, in order to let the solar-generated electricity be cost equivalent with the gas-generated electricity, a carbon trading price of \$432.87/ton would be needed. However, this price is about 20 times higher than the current carbon trading price in Europe (~\$21.30/ton [143]), and about 8 times higher than the predicted price in 2016 (~\$56.83/ton [144]). Therefore, it is very unlikely in the foreseeable future that Singapore's carbon trading price can be so high.

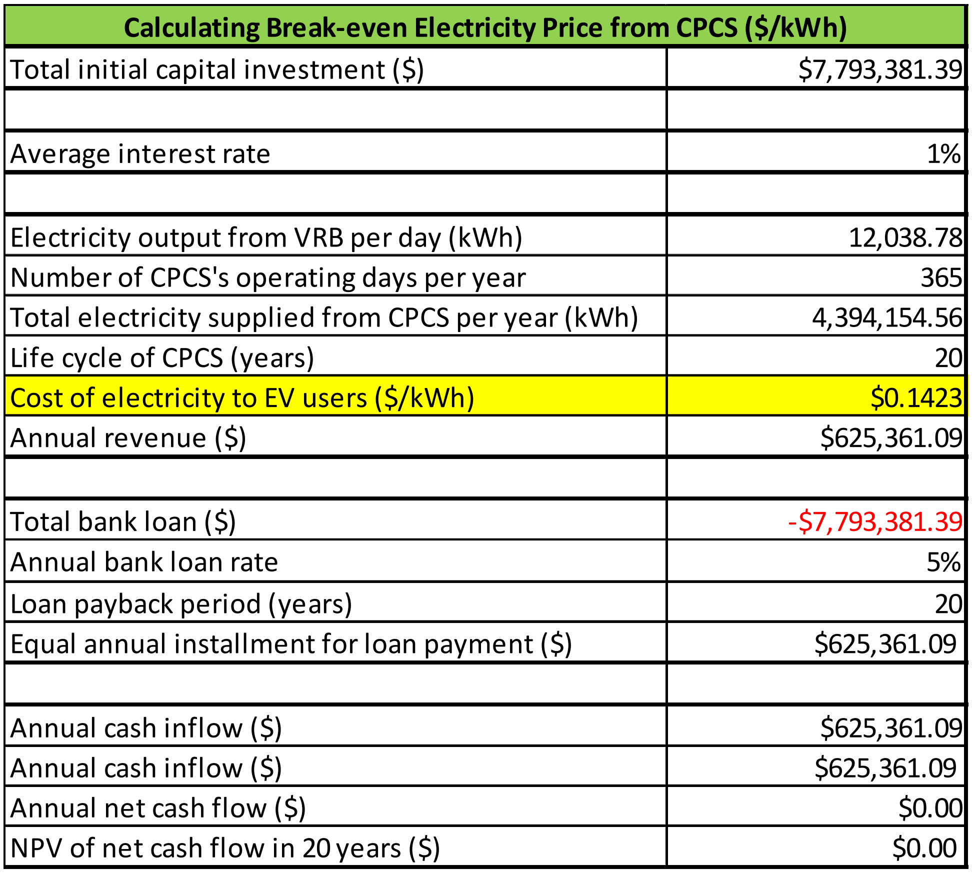
In order to estimate the lower limit of the break-even electricity price from CPCS installed in IMM building, a "best case" analysis is conducted. There are two major changes to the previous cost model.

(1) There will be a one million equivalent to \$694,444.44 USD government financial support

to offset partially the initial capital investment of the CPCS. This is based on the news release from the Economic Development Board (EDB) in 2008.

(2) There will be no energy storage system implemented together with the solar PV panel systems. This is based on the assumption that the electricity generated at daytime can be 100% utilized or charging EVs instantaneously after it is generated. As a result, there will be no charging at night or during cloudy days, and there will no energy loss due to the storage system energy efficiency. The cost associated with the extra power conditioning system for smoothing the energy output from PV panels will be incorporated into the final DC/AC inverter cost. Therefore, the initial capital cost only includes the cost for solar PV system.

The final cost model parameters used to calculate a break-even electricity price are shown in Figure 59.



Calculating Break-even Electricity Price from CPCS ($/kWh)	
Total initial capital investment ($)	$7,793,381.39
Average interest rate	1%
Electricity output from VRB per day (kWh)	12,038.78
Number of CPCS's operating days per year	365
Total electricity supplied from CPCS per year (kWh)	4,394,154.56
Life cycle of CPCS (years)	20
Cost of electricity to EV users ($/kWh)	$0.1423
Annual revenue ($)	$625,361.09
Total bank loan ($)	-$7,793,381.39
Annual bank loan rate	5%
Loan payback period (years)	20
Equal annual installment for loan payment ($)	$625,361.09
Annual cash inflow ($)	$625,361.09
Annual cash inflow ($)	$625,361.09
Annual net cash flow ($)	$0.00
NPV of net cash flow in 20 years ($)	$0.00

Figure 59 Calculation of break-even solar-generated electricity price in the “best case”

The break-even price in the “best case” is therefore $0.1423/kWh (P1), about 1.5 times of the annual average electricity price in the past five years and about the same as the highest historical electricity price during the same five-year period. Based on the average electricity price (P2) of $0.0932/kWh, the price differential is $0.0491/kWh. The corresponding carbon trading price to let P1 and P2 equal is calculated as:

$$\frac{\$0.0491/\mathrm{kWh}}{442.86\mathrm{g}/\mathrm{kWh}} \approx \$0.11087/\mathrm{kg} = \$110.87/\mathrm{ton}$$

This price is still about 5 times higher than current carbon trading price in Europe and about 2 times of the predicted price in 2016.

6.3.6 Summary

In conclusion, the final cost ($0.2849/kWh) those private EV users have to bear for using electricity generated from the SSEGS-ES system built in IMM building is too high to be accepted by the consumers. With the “best case” analysis in which there is government’s financial support and no energy storage system is needed, the price of electricity from solar PV panels ($0.1423/kWh) can match the highest historical electricity price in the past five years in Singapore. Therefore, only with gas-generated electricity price above $0.1423/kWh, the solar-generated electricity will be more attractive to private EV users. Furthermore, this conclusion is drawn based on the assumption that the electric vehicles can only be charged at car parks when there is sunlight available. Sometimes, this might not be the most convenient to EV users.

6.4 Grid-tied PV-EV System (GPES) for Large Scale Solar Electricity Generation in Singapore

6.4.1 Background

To promote environmental friendly transportation in Singapore, the economics of transportation with Electrical Vehicles (EV) have been studied (refer to Fu’s thesis), which includes the BEV model for taxi based public transportation and PHEV model for private vehicle transportation. As more than 97% of the electricity generation in Singapore are currently from non-renewable energy resources which mostly consists of natural gas and fuel oil[145], green electricity generation model based PV systems was analysed with the fact that solar energy is relatively abundant in tropical Singapore(refer to Sun’s thesis). It has been shown that with government rebate of less than 35% of the total system cost, a PV system in its current stage of technical development with a capacity larger than 70kW can be a profitable investment, under the present government policy of equal electricity pricing. In order to determine the economic feasibility and environmental benefits of feeding solar electricity to EVs, solar PV integrated EV charging system shall be modelled and evaluated.

The first model of the PV-EV system is built in a carpark as a standalone system where solar panels are installed on the roof of the carpark and charging spots are built around the parking lots. This model has been evaluated in previous sections as the Car Park Charging System (CPCS) model.

The second model of a PV-EV system is to build a large scale grid-connected PV system which feeds electricity to the grid at the electricity wholesale price. The EVs will get electricity directly from the grid. The objective of such a model is to determine whether it is economically feasible for an operator to install a large scale PV system whose electricity output could offset the electricity consumption of all private electrical vehicles (PHEV). The following analysis will be dedicated to this Grid-tied PV-EV System (GPES) model.

6.4.2 Methodology

In the GPES model, an aggregate roof area of state developed buildings is estimated, which will set an upper limit for the total area available to install PV panels as one integrated system by a single land use license. As electricity cost from larger systems is generally less than that from small systems due to price discount or minimal incremental cost, a system based on such an area will be calculated. The size of the area required to be able to charge all the EVs in Singapore will also be estimated and compared with this area upper limit to see how many EVs such a system can support. A feasible system based on practical restrictions will be determined and discussed in detail.

With such system estimations, the cost of electricity in terms of $/kWh will be calculated. This Grid-connected unit cost (Pg) will be compared with the utility Wholesale electricity price (Pw) and the conventional Combustion Engine vehicle (Pce). Similarly with the standalone CPCS model, the price comparison will enable us to determine the EV users' acceptance level as well as the economic feasibility of such a system with and without government incentives. Polices can also be suggested respectively to promote such a system.

6.4.3 Assumptions

The following assumptions are made in the detailed evaluation of the GPES model:

(1) The solar panel specifications used in this analysis is based on the CdTe thin film modules evaluated in Sun's thesis. The capital cost modelling of building such a solar PV system is also obtained from that thesis.

(2) The specifications of EV batteries and charging parameters are obtained from Fu's thesis

on EV battery evaluation. Based on his thesis, it is assumed that Plug-in Hybrid Electric Vehicle (PHEV) is the most suitable model for private transportation-in Singapore. Herein, PHEV is used together with the GPES model as the model is based on private cars. The PHEVs are assumed to need to charge only once per day.

(3) The PV system is estimated to be able to operate for 20 years. An initial capital investment is assumed where changing of parts with lifetime shorter than this operation time will be discounted back to the Present Value (PV). Thus Net Present Values (NPV) of revenue and cost will be used for comparisons. The investment interest rate is set at 1% and the inflation rate is assumed to be zero in Singapore for discounting purposes. The lump-sum capital investment is taken from a bank loan with annual interest rate of 10%. The loan is paid back with equal annual instalment for the next twenty years. The annual instalment is likewise discounted back to the present value.

(4) The installation area will be leased by the government to the GPES operator for an annual royalty fee. The operator will install this solar PV system and sell electricity to the grid for revenues. The operator can be any individual or corporation or any other kind of investor.

6.4.4 Cost Model

Total Available Area Estimation

The largest portion of the state owned land area is used for residential and commercial developments. As the Housing Development Board (HDB) residential blocks are standard government built buildings which have roofs that are mostly non-shaded due to the multi-storey height, it is reasonable to take all the HDB roof areas as an aggregate unit to estimate the maximum allowable roof areas of the PV system.

According to the Housing Development Board, the total number of residential units under HDB's management is 885, 140 as of 31 March 2008[146]. Based on an average of 15 residential floors for each HDB block with 6 residential units on one floor, the total number of units per block is 90. Thus the number of blocks in total is around 9835. Then based on the assumption in Sun's thesis that there is one multi-storey carpark every 4 HDB blocks of residence and such a unit has an estimated area of 3870m^2. Taking into consideration of the carpark shading and the non carpark integrated old buildings, we can take half of the car park area, which gives an average area of 3225m^2 for the 4HDB-Carpark unit. Thus with 9835 blocks, the total number of such unit is around 2459. The total available area is thus estimated to be around 7.93km^2. The detailed estimations are shown in Table 33 and Table 34.

	No. of 4-room flat	No. of 5-room flat
	4	2
Standard Area(m2)	85	110
Floor Area(m2)	340	220
Flat Floor Area(m2)	560	
Excess Area(m2)	85	
1 HDB Roof Area(m2)	645	
Total HDB Roof Area(m2)	2580	
Car Park Roof Area (m2)	645	
Total Roof Area of a 4HDB-Carpark Unit (m2)	3225	

Table 33 Average Area Estimation for an HDB-Carpark Unit

	Till 31-Mar-08
HDB Dewling Unit in 2008	885,140
Residential Floors per HDB block	15
units per floor	6
Number of Units per Block	90
Number of Blocks	9835

Number of HDB-carpark Unit	2459
Total area (m2)	7929379.17
Total Area (km2)	7.93

Table 34 Total Available Area Estimation for the GPES Model

Area Requirement for the PV System to Charge All Private PHEVs

The PHEVs are driven by advanced Li-ion batteries which can be plugged into any normal power socket that provided 240V AC power supply. The characteristics of the model of Li-ion batteries are elaborated in Fu's thesis and reference [139], as shown in Table 35. To be consistent with the previous models, the charging efficiency is assumed to be 90%.

By the end of 2007, total number of private cars in Singapore is 451,745[147]. If all these cars are replaced by PHEVs or a 100% market penetration, then the total charging energy requirement for one day will be 8.8kWh*451,745/90%, which is 4417.06 MWhs. As the solar panels are at a 10% efficiency with an 20% percent system loss for a grid-tied PV system, the energy production per day from 1m^2 solar panel is 1000W/m2*10%*80%*4 peak hours, which is 0.32kWh. Thus the area needed to output 4417.06 MWhs of energy per day with a 90% panel overhead is 4417.06 MWhs/0.32/90%, which is around 15.41km^2. The details are shown in Table 35. As this area is more than twice the total available area of 7.93km^2, the GPES system based on HDB residential unit is only able to supply around 51.4% of market penetration.

Battery Capacity (kWh)	15
Depth of Charge/Discharge (kWh)	8.8
Charging Voltage (AC Volts)	240
Charging Current (Amp)	7.5
Charging Power (kW)	1.8
Charging Time (hrs)	4.89
Solar Irradiance(W/m2)	1000
Daily Peak Hours (hrs)	4
Solar Module Efficiency	10%

System Efficiency	80%
Total energy per day per m2 of panel (kWh/m2)	0.32
Number of private cars	451,745
Market penetration	100.00%
Total no. of PHEVs	451745
PHEV Charging efficiency	90%
Total energy required (kWh) per day	4417062.22
Panel area needed (m2)	13872595.72
Percentage overhead	90%
Total area needed (m2)	15413995.24
Total area needed (km2)	15.41

Table 35 Total Required Area Estimation to All Private Cars (PHEV)

Electricity Cost Estimation

Based on an available roof area of 7.93km^2, with the same grid-connected model that was discussed in Sun's thesis for the HDB-Carpark residential model, the total production capacity is as high as 568MW. The cost of such as system is more than 2.88 billion Singapore dollars. The electricity cost is estimated as US $0.121/Wp, as shown in Table 36.

Cost Calculation	
Module Cost ($)	1427288250.00
DC/AC Inverter Cost ($)	392367102.35
Installation Cost ($)	181965535.24
NPV of Maintenance and Licensing Cost ($)	11529.10
Total Cost (USD)	2001632416.69
installed cost per watt (USD)	2.80
Electricity Cost (USD /kWh)	0.121

Table 36 Total Cost Estimation of a Grid-tied HDB-Carpark PV System

In terms of percentage cost as shown in Figure 60, the module cost is the highest part of cost that accounts for 71.3%, which is reasonable for such a large scale grid-connected system. Again the next big component is the inverter cost which is 19% in this case. The maintenance cost is almost negligible due to the size of the system. Even when the maintenance cost is set as 1 million USD per annum, its share of percentage cost is still minimal, as shown in Figure 61.

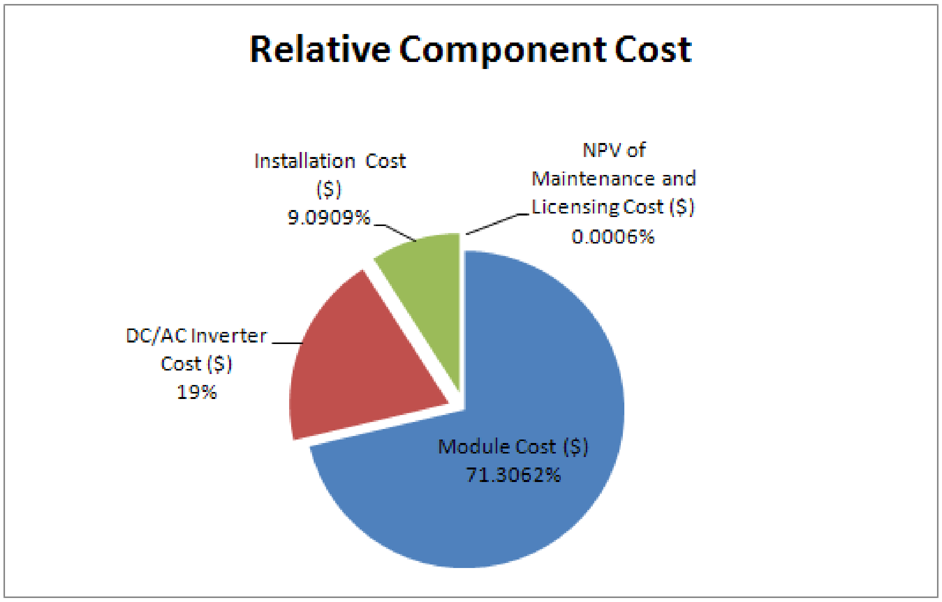


Figure 60 Relative Percentage Cost of GPES

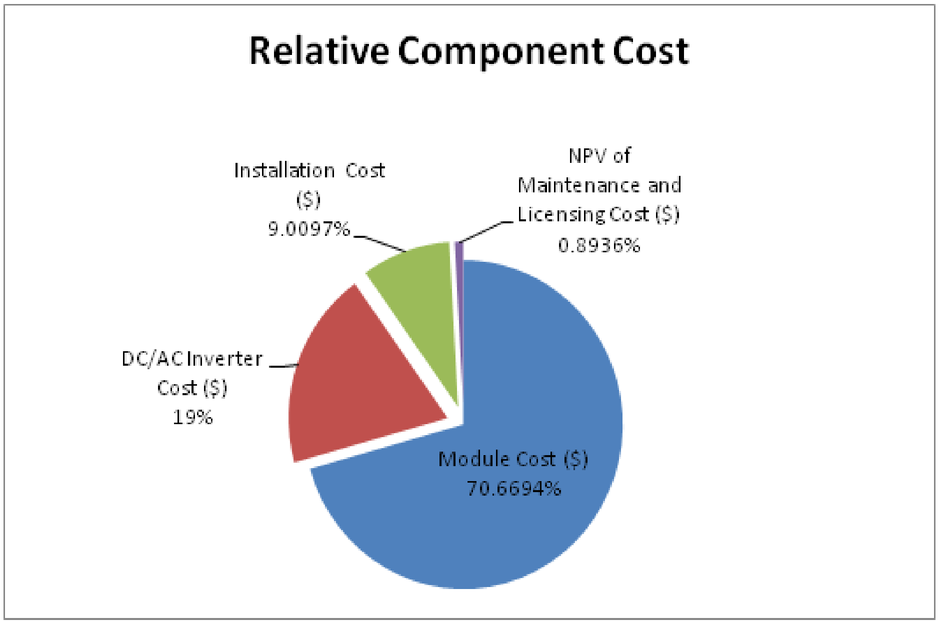


Figure 61 Relative Percentage Cost of GPES with High Percentage of Maintenance Cost

Analysis for a Practical System of 50MW Capacity

Though Singapore has such a potential to achieve more than 568MW capacity, however there is a limit for the amount of power to inject into the grid in order to avoid grid stability and reliability issues. In Singapore, the regulations on grid transmission are set by Energy Market Authority (EMA), which is acting as the Power System Operator (PSO) of Singapore. In the latest version of the Electricity Market Rules published on 1 July 2009, there hasn’t been specific documentation of non regulated electricity such solar electricity or wind[148]. Thus here the electricity feeding limit to the grid is set as 50MW which is the amount currently required for general grid reliability[148] with a peak grid transmission level of around 6GW and a generation capacity of around 9.775MW[149].

Electricity Cost Estimation

Based on the grid-connected PV system analysed before, the area needed for 50MW capacity is around 697900 m^2. As the area is around 100 times larger than the area increase compared with the grid-tied HDB-carpark model from Sun’s thesis, the maintenance cost per annum is assumed to 100 times larger as well, which is shown in Table 37.

Maintenance and Licensing Cost	
Maintenance Price($/year)	50000.00
Licensing cost ($/Year)	138.89
Total Variable Cost ($)	50138.89
NPC Cost over life time ($)	904783.98

Table 37 Maintenance and Licensing Cost

For such as system, the electricity cost didn’t change much as compared with the previous case, shown in Table 38. The total capital cost is now around 177 million US dollars. Among all the cost, the module cost is still the largest part as shown in Figure 62, which is the general case for grid-connected systems.

Cost Calculation	
Module Cost ($)	125622000.00
DC/AC Inverter Cost ($)	34533977.37
Installation Cost ($)	16015597.74
NPV of Maintenance and Licensing Cost ($)	904783.98
	USD
Total Cost (USD)	177076359.09
installed cost per watt (USD/Wp)	2.82
Electricity Cost (USD /kWh)	0.121

Table 38 Cost Estimation for a 50MW Generation Capacity

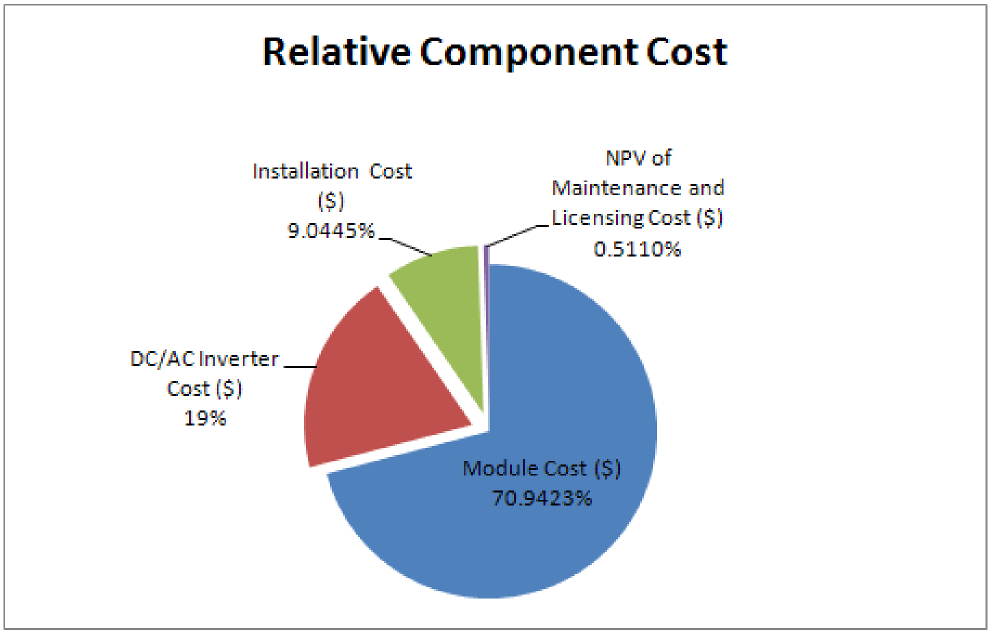


Figure 62 Relative Percentage Cost of GPES with 50MW Capacity

Revenue and Profit Estimation

The average electricity wholesale price is at US$0.109/kWh quoted from Sun's thesis and it will be used for revenue estimation. As the yearly energy production is around 72,996,890 kWhs, the yearly revenue will be around 7.96 million US dollars (72,996,890 kWhs x $ 0.109/kWh. Discount the 20 years' revenue back to the present value, the Net Present Revenue is 145.06 million US dollars. Deducting the cost of 177.08 million US dollars, there is already a net loss without financing the capital investment. The details are shown in Table 39.

	USD
Total Cost	177076359.09
Revenue	145055128.44
Profit	-32021230.64

Table 39: Revenue and Profit Estimation

6.4.5 Economic Feasibility Analysis and Environmental Benefits

Investment Evaluation for the Solar Operators with Government Rebate or Price CO_2 is evaluated in this section. As this system is not profitable, it is not considered as a good investment without government incentives. If considering government rebate, it is found that if the government offsets 18.08% of the initial cost, the investment will breakeven to begin to gain profit, as shown in Table 40. If consider financing the initial total capital cost of 177.08 million US dollars with a loan from bank at an interest rate of 10%, the annuity payment will be 20,799,322.69 US dollars. The Net Present Value of all annuities is calculated as $474,124,804, which is the actual capital cost. With this amount of cost, the government rebate has to be increased to 69.41% to breakeven even.

	Government Rebate
	18.08329%
	USD
Total Cost	145055127.55
Revenue	145055128.44
Profit	0.89

Table 40 Government Rebate to Breakeven

To evaluate whether the investment is economical, we also have to compare the gain from this PV system with other type of investments. With the 1% interest rate assumption, an investment return of 1% from the capital investment is the Opportunity Cost[2]. The case without

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[2] Opportunity Cost= the Cost of the Second Best Alternative

external financing will be first considered. Thus based on the capital investment of USD 145 million after the 18.08% government rebate, the Net Present Value (NPV) of the yearly return is US$26.2 million, as shown in Table 41. For this system to be economically feasible, the government rebate has to be increased to 30.61% of the initial cost in order to make the GPES system an economically profitable investment. As shown in Table 42.

In the case with external capital cost financing, the economical profitability model is no longer valid, as the operator does not own this amount of money, thus cannot make investments with it.

	USD
Capital Investment	145,055,127.55
Interest Rate	1.00%
NPV Rate for 20 Years	18.05
NPV of Return from Capital Investment	26,175,999.87

Table 41 Opportunity Cost Calculation with a Breakeven Government Rebate

	Government Rebate
	30.60585%
	USD
Total Cost	122880637.78
Revenue	145055128.44
Profit	22174490.66
Capital Investment	122880637.78
Interest Rate	1.00%
NPV Rate for 20 Years	18.05
NPV of Return from Capital Investment	22174490.58
Net Economic Profit	0.09

Table 42 Government Rebate to be economically profitable

Currently, the government rebate policy for solar PV system is stated by EDB in the solar capability scheme, which gives a rebate of 30 to 40% of the total capital investment, but capped at 0.6944 million US dollars[150]. As the above cases all require 10s of millions US dollar rebate, the GPES system will not be an economical investment at the current stage of technical development.

Investment Evaluation with Electricity Price Commission

It is assumed that government gives a clean energy electricity commission and buys the PV electricity fed to grid at a higher price. Without external financing of the US$177 million capital cost, the price for the solar electricity sold has to be US$0.133/kWh in order to breakeven, as shown in Table 43. Similarly with previous cases, to make it economically preferable as compared with the alternative investment, the price has to be US$ 0.158/kWh, as shown in Table 44. The profitability versus electricity price is plotted in Figure 63 and it is seen that the crossover points at the nominal profitability line and the economic profitability line which corresponds to the cost breakeven and economic profitability breakeven points.

	USD
Electricity Price (/kWh)	0.133
Government Rebate	Government Rebate
Total Cost	177076359.09
Revenue	177076359.41
Profit	0.32

Table 43 Price Commission to Breakeven

	USD
Electricity Price (/kWh)	0.158
Government Rebate	0.00000%
Total Cost	177076359.09
Revenue	209030768.00
Profit	31954408.92
Capital Investment	177,076,359.09
Interest Rate	1.00%
NPV Rate for 20 Years	18.05
NPV of Return from Capital Investment	31,954,408.17
Net Economic Profit	0.75

Table 44 Price Commission to Be Economically Profitable

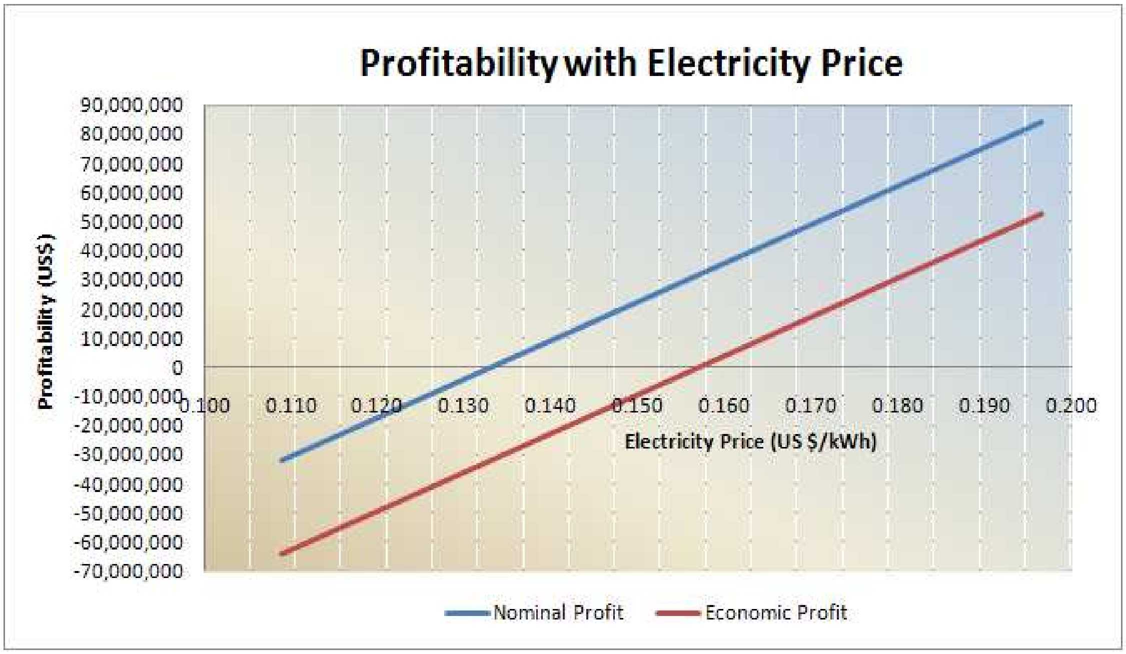

Figure 63 Profitability of GPES VS Electricity Price

Electricity Price Sensitivity with System Size

All the above analysis has been based on the 50MW capacity. As the electricity price of a grid tied system is related to its size, the size dependence of electricity price is plotted in the following figure. As we can see that electricity price drops fast with in the first 30 to 40MW size range, once it exceeds that, the electricity will stabilize at around US$0.121/kWh.

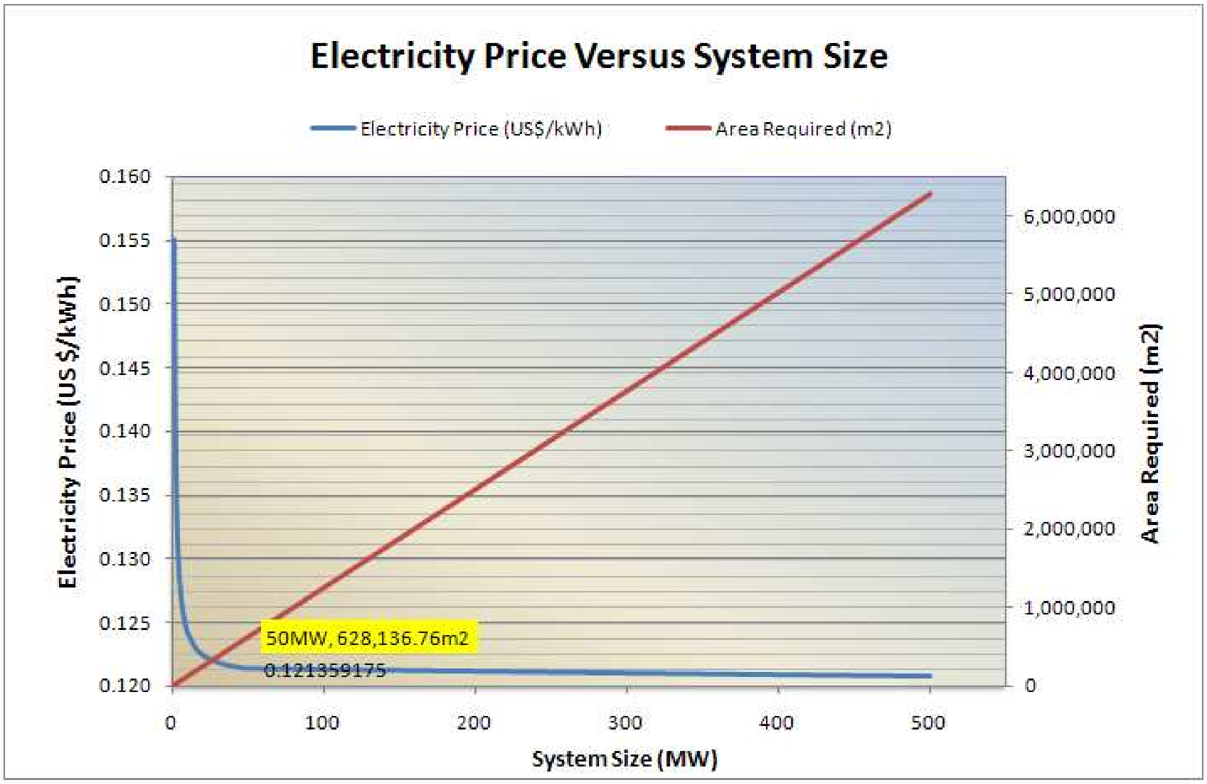

Figure 64 Electricity Price Vs System Size for a Large Scale PV System

Carbon Dioxide (CO2) Emission Reduction

From the above analysis, it is apparent that the electricity generated from a large scale grid-tied PV system in Singapore is still too expensive without any government incentives. And it will be not able to compete with current grid electricity price which is at almost half of the PV electricity cost. PV electricity thus will not be attractive to PHEV users at the PV system's current stage of technical development.

However, the main advantage of solar electricity lies in its clean and renewable resource. And it is environmental friendly with zero emission as compared to the current grid electricity which is mostly generated from non-renewable fossil fuel resources such as nature gas and oil, as described in Part one of the project and in the previous CPCS model.

With global environmental concerns as one of the most important issues in the world, every government has the responsibility to reduce green gas emission, among which CO2 is a key component. To ensure global environmental sustainability in the long term, restriction on CO_2 emission shall also be put forward by the Singapore government. As mentioned in the previous models, this can be done in the form of carbon credit trading system seen in some European countries. Similarly with before, the environmental benefits of grid-tied PV electricity shall be analysed based on the carbon trading system mentioned previously.

As the carbon intensity of the current grid electricity is 434g/kWh, and the price of electricity from the 50MW GPES is US\$0.1213/kWh, and the utility (gas-generated) average wholesale electricity price is US\$0.1090/kWh, so the price difference is US\$0.0123/kWh. Similarly, to bridge this price gap, the CO2 emission per kWh of gas-generated electricity needs to be charged. The unit carbon price is therefore:

$$\frac{\$0.0123/\mathrm{kWh}}{434.0\mathrm{g}/\mathrm{kWh}} \approx \$0.02834/\mathrm{kg} = \$28.341/\mathrm{ton}$$

Hence, in order to let the large scale grid-tied electricity’s price competitive with the gas-generated utility electricity’s price, the break-even price of CO2 should be \$28.341/ton, which is lower than a stand-alone model where storage is required.

From the previous section, a carbon trading price of \$28.341/ton is needed in order to make the grid-tied solar electricity be market competitive with the gas-generated electricity. This price is about 33% higher than the current carbon trading price in Europe (~\$21.30/ton [143]), but is much less than the predicted price in 2016 (~\$56.83/ton [144]). Therefore, solar electricity from a large scale grid-tied tied PV system can be competitive with the utility electricity in the near future.

6.4.6 Summary

To summarize, in the 50MW Grid-tied PV-EV Electricity System (GPES) just analysed, the cost of US$0.1215/kWh is still too high for solar electricity to compete with the current gas generated utility electricity at a whole sale price of US$0.109/kWh without any government incentives. As the cost of such a system is around 255 million Singapore dollars, even with the maximum government rebate of US$694,444.44 at present, the change to the electricity cost per kWh is insignificant due to the huge size of the base. However, if the government is willing to bear an electricity price commission to offset the additional cost, or force a higher buying price to the grid at US$ 0.133/kWh, which is higher than the current electricity wholesale price, the PV electricity can be competitive with the current utility electricity price at its current stage of technical development.

Without government incentives, the electricity cost can be offset by some amount through carbon trading with its reduction of CO2 emission. It was found that a $7.0/ton increase above the current carbon trading price of ~$21.30/ton is required to offset the difference between PV electricity cost and the current utility electricity wholesale price. Based on the carbon trading price trend, we foresee the competitiveness of solar electricity generated from large scale grid-tied PV system. Electrical Vehicles can then run on green electricity to promote a green transportation system in Singapore.

6.5 Concluding Remarks on the Implementation Models in Singapore

Based on the four implementation models, a few concluding remarks can be drawn about the prospects of the green technologies evaluated in this group Project.

6.5.1 Environmental Benefits

As shown in the Swapping Station Model, a BEV taxi can reduce 25-31 tons of CO_2 emission every year. A penetration of 5% in the taxi market (a total of 1250 BEV taxis) would mean at least 31 kilo tones of CO_2 reduction. This reduction can be further increased to more than 38 kilo tones, nearly 0.1% of the total CO_2 emission in Singapore, if renewable energy is used to power up BEVs. At higher BEV taxi penetration rate, the environmental gains will increase further. From the Private Car model, a PHEV user who drives 40 miles a day is able to achieve 3.0806 tons of CO_2 reduction per year. Since private car sector is the largest in the automotive market in Singapore, replacing gasoline cars with PHEV for private car users is a key to the CO_2 reduction in transportation sector.

Electric vehicles are still at its early stage of development. It is expected that these “green” cars’ fuel efficiency will be continuously improved along with the booming green vehicle industry. At the mean time, the rapid development of PV technologies could also lead to PV panels of higher efficiencies at lower cost. As a result, these environmental gains of electric vehicles and the electric vehicles plus renewable energy system can be further enlarged in the near future.

6.5.2 Political Benefits

Politically, with a electric vehicle system in place, Singapore can demonstrate to the world its determination to reduce the absolute carbon emission in order to meet the Kyoto Protocol requirement. Singapore has a high CO_2 emission per capita, reflected by its high energy consumption. Figure 65 shows the energy consumption per capita for a few selected countries including Singapore. This graph is plotted based on statistics from Energy Information Administration (EIA)'s International Energy Statistics and International Energy Agency (IEA)'s Key World Energy Statistics 2008 [151]. The large difference between these two sets of data for Singapore is mainly because that the former takes into account of energy consumed by marine bunkers at the Singapore port. Nevertheless, both data suggests that as an oil refining center, this small island country has a high energy consumption rate per capita, which is at the same level as other developed countries. Singapore is one of the Annex-B countries in the Kyoto Protocol. Therefore, Singapore does not hold any imperative obligation in reducing its absolute GHG emission as compared to countries in Annex-A list in the first phase before 2012. However, the high GHG emission has brought many pressures to Singapore. BEV system, on the other hand, will help improve the image of this highly industrialized city state, and demonstrate the government's resolution toward environment protections.

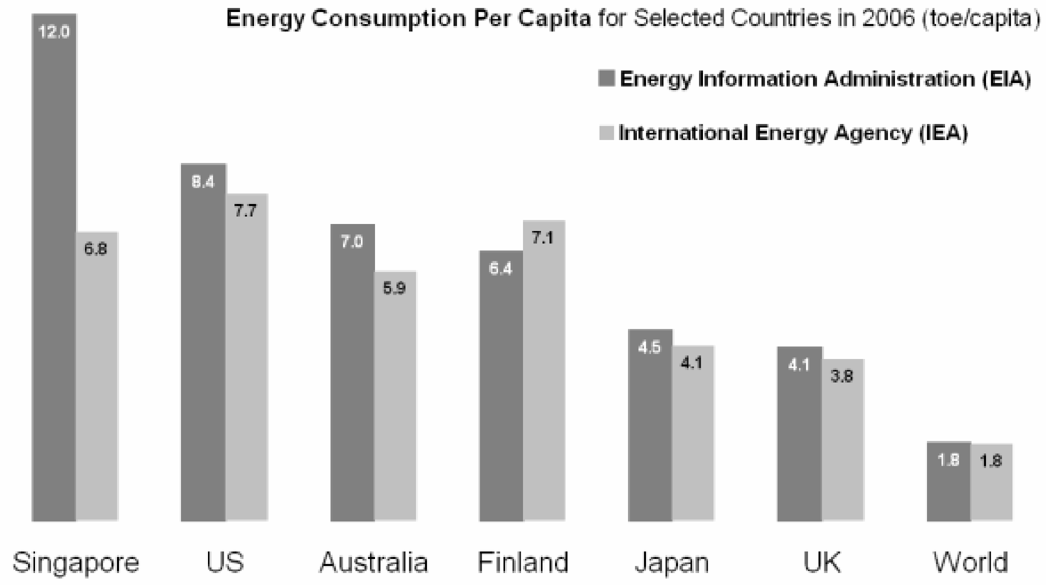

Figure 65 CO2 Consumption Per Capita for Selected Countries in 2006[151]

6.5.3 Social Benefits

Socially, implementing electric vehicle system helps to raise the awareness of environmental conservation and it also helps Singapore to maintain its status being a green and clean city in the world. The low noise level of XEV compared to conventional cars can greatly enhance people’s driving experience, reduce noise pollution in city areas and project an environmental-friendly image of Singapore to the world.

6.5.4 Economical Barriers

Implementing electric vehicles requires a large amount of upfront capital cost as compared to gasoline cars. Government incentives are necessary to help introduce electric vehicles into the Singapore market. However, the largest barrier also lies in this high capital cost.

While the government incentives are essential for implementing electric vehicles, the Singapore Government does not reap many economic benefits from this system. Firstly, the major cost of XEV systems is from battery. Battery suppliers are mainly from Japan, Korea, China and U.S. In Singapore, there is rarely any industry directly related to battery manufacturing. Secondly, one important consideration to promote electric vehicles in U.S. is to save its automotive industry. Unfortunately, Singapore does not have its own automotive industry either. All the vehicles in Singapore are imported from other countries. Moreover, while construction of battery swapping station can possibly create some employment opportunities in Singapore, the major cost in these stations is from the battery swapping mechanics, which are likely to be manufactured in other countries. Lastly, the operation of battery swapping stations is developed towards an automatic system. This is to minimize staffing cost and make the process more convenient for BEV drivers. However, such operation requires very little manpower, thus does not create many employment opportunities in Singapore.

In the development of solar industry in Singapore, so far there is no policy in place to specify a certain percentage of electricity which must be from the renewable energy by a certain time; there is no sign showing that the government will provide feed-in-tariff for solar electricity as well. Instead, the government emphasizes that “energy cost should be borne in full by end-users”, because the government believes that subsidization would “dampen price signals and create the incentives to over-consume” [152]. However, the solar electricity is still too expensive to be accepted by most users at its present price level. The estimated present price level of \$0.1215/kWh is based on the cost effective large grid-tied PV system at its state of the art technology.

It appears that the Singapore Government put more focus on growing the industry to create more employment opportunities and generating revenue, rather than emphasizing the PV application in Singapore. Therefore, a large scale of deployment of PV probably will not happen in a short term. It is more likely that the government will wait for the cost of this technology to go down.

6.5.5 Summary

In a nutshell, despite of environmental, political and social benefits, currently the high cost of electric vehicle system prevents it from entering the Singapore market easily, as the government support is not strong enough. Under current policies, battery swapping model and private car model are not cost-effective compared with their gasoline counterparts. However, this situation would change if gasoline price goes up, or if the government taxes the CO_2 emission.

\$70.21/ton CO_2 price is necessary to make the cost of BEV taxi system competitive to that of gasoline taxi system. With increasing CO_2 trading price, it is highly possible to see BEV taxis running on the road in next ten years. On the other hand, \$378.3445/ton CO_2 price is needed for

PHEV to breakeven. This is 17.5 times of the current CO_2 trading price in the EU. As the private cars contribute the most CO_2 emission in the transpiration sector and PHEV fits the needs of private users well, further rebate must be given for PHEV to be accepted by Singaporeans.

Solar energy could provide “clean” electricity for the XEV system and maximize its environmental benefits. Currently only a few trial sites are built to study the feasibility of roof-top PV in Singapore, and a long time into the future is required for PV electricity to be competitive with utility electricity.

With energy storage system, the electricity generated from solar energy can have better quality and longer available usage time (not only during sunny daytime.) However, the cost of solar energy and storage system at present level is still too high to be generally accepted in Singapore. Again, it is expected that with increasing oil price volatility and reduced technology costs, solar energy with storage system can start to have its market niche in the future.

In the best scenario, electric vehicles, solar PV and storage technology will become mature during the same period. A combination of them would generate the maximum benefits. For example, a total of only 1250 BEV taxis running on solar electricity could save about 38 kilo tons of CO2 per year. If the oil price rises rapidly within a short period, it is possible to have a electric vehicle system relying on fossil fuel generated electricity. In this scenario, these 1250 BEV taxis can still reduce CO2 emission by 31 kilo tons every year, compared to gasoline cars. Before that, the best way in reducing CO2 emission from the transportation sector is probably promoting public transport.

6.6 Implementation Models in Singapore Group Project Conclusion

In this project, the car, energy and solar energy (electricity) market in Singapore are evaluated at the first stage. While the car population in Singapore is strictly under control by the government through various policies, the car demand remains strong in Singapore. Seeing the positive environmental impacts of green vehicles, the Singapore government also introduced "green vehicle rebate" to encourage the growth of green vehicles in Singapore. Although the total quantity of green vehicles remains small, the growth rate in recent years has been quite significant. For example, the number of hybrid cars was almost doubled from 1057 in Year 2007 to 1999 in Year 2008. Secondly, it is noticed that Singapore relies heavily on natural gas imported from neighboring countries for its electricity generation, which consists of nearly 76% of its electricity fuel mix. Singapore has an urgent need to diversify its electricity mix. On the other hand, its total installed electricity generation capacity of about 10 GW is almost twice of its peak demand. This excess power generation capacity can potentially provide electricity for the XEV system. Lastly, the government is also heavily investing in solar industry. While most of photovoltaic panels made in Singapore are for export, the government is investigating the application of building integrated photovoltaic (BIPV). This renewable solar energy can be another source of electricity generation. It can also provide "green" electricity to the XEV systems to make these vehicles truly "green".

To further understand the economics and feasibility for generating renewable energy, both photovoltaic and solar thermal technologies are investigated.

For photovoltaic systems, it is found that at the current stage of technological development, the cost of modules and inverters take the largest part of the total system cost. Among all types of solar cell and module technologies, crystalline Si based PV technology has the best performance in terms of efficiency and system reliability, while thin film technologies have the lowest cost.

It is also found that concentrating solar thermal technologies is not suitable for Singapore. Firstly, in Singapore about 40% of its daily radiation belongs to diffuse radiation; only an average of $2.4\,\mathrm{kW/m^2}$ direct normal insolation (DNI) is available daily. Secondly, CSP plants occupy a large area to collect solar radiation. It is impractical for Singapore to have such a large area just for building a power plant because of its limited land. These two factors make the concentrating solar power technology unsuitable for the Singapore market.

Large-scale energy storage system using flow battery technology, more specifically the vanadium redox flow batteries (VRB), is also evaluated. VRB is one of the most promising candidates in the flow battery family meeting the future demand, mainly because of its environmental friendliness and decreasing unit capital cost. However, based on the models presented in the project, implementing flow batteries system for large-scale energy storage in Singapore is still not very financially viable at present at this moment. The main obstacle is the cheap energy (electricity) cost in Singapore.

Since battery will be the most critical part for electrical vehicles, lithium ion battery technologies are examined in order to choose one specific battery technology to meet the technical specifications. It is found that both manganese and phosphate based lithium ion batteries are potentially suitable for electric vehicles. With higher durability and lower cost, $LiFePO_4$ battery is expected to have higher utility for electric vehicles.

Based on these findings, four different models are built and evaluated. In the first model, battery electric vehicle (BEV) is identified as a suitable candidate to replace gasoline taxi because it offers reduced CO2 emission, and lowered noise level especially in a long driving distance. This BEV taxi system will be implemented together with battery swapping stations as supporting infrastructure. From the economic analysis, it is found that based on the average electricity and gasoline price from 2005 to 2009 ($0.093/kWh for electricity and $1.86/gallon for gasoline), the cost per mile for BEV and gasoline car is $0.217 and $0.199, respectively. To bridge this price gap, a carbon tax of $70.21/ton is required to be placed on gasoline taxis. On the other hand, when the gasoline price rises above $2.4/gallon, BEV taxi will become more competitive than gasoline taxi in terms of cost per mile. Furthermore, each BEV taxi can help to reduce about 25 tons of CO2 emission every year. This reduction can go up to 35 tons if the electricity is generated from renewable source instead of natural gas fired power plant. Therefore, if all the gasoline taxis are replaced by BEV taxis, a total of 855.61 kilo tons of CO2 reduction can be achieved. This will be about 2% of the total CO2 emission in Singapore (40, 377 kilo tons in 2005).

In the second model, PHEV is found to be suitable for private users for its acceptable up-front price, less CO2 emission and lower operation cost. By using the same gasoline and electricity prices as in the first model, the model has shown that the cost of PHEV is still higher than that of gasoline car under current Green Vehicle Rebate scheme. In order for PHEV to be cost equivalent with gasoline cars, a CO2 trading price of $378.34/ton is needed and this is 17.5 times of the current CO2 trading price ($21.6/ton) in the EU. Hence, PHEV is unlikely to be adopted by private users unless more incentives are given by the government.

In the third model of car park charging system (CPCS), a stand-alone solar (PV) electricity generation system with energy storage is built for a car park charging system (CPCS) in a large shopping complex in the south-western Singapore. Based on a cost model of making full use of the available roof-top area for solar PV panels (>34,000m2) and charging electric vehicle at maximum electricity storage capacity (2.5MW, 10MWh), the final electricity cost from the CPCS is about $0.285/kWh. This is about three times of the average gas-generated electricity price in Singapore from 2005 to 2009 ($0.093/kWh). In order to make the CPCS-generated electricity cost equivalent to gas-generated electricity, carbon credit should be awarded and the calculated breakeven CO2 price is about $432/ton. This figure is about 20 times of the current carbon trading price in the EU and 8 times of the predicted price in 2016. A “best case” is also carried out in which the energy storage system is excluded and government’s financial aid is considered. The final result shows that only with gas-generated electricity price above $0.1432/kWh, could the CPCS become economically feasible. However, the trade-off in the “best case” would be the less availability of electricity when there is no sun-light available.

In the last model of a large-scale grid-tied PV-EV electricity System, the economic feasibility of building a 50MW large-scale grid-connect PV system with the state of the art technology on the top of HDB roofs has been considered. The total area required for such a system is 697,900m2 and the cost is around 255 million Singapore dollars. The cost of electricity without any government incentives is around US$0.121/kWh, higher than utility electricity wholesale price at US $0.109/kWh. If considering the maximum government rebate of 0.6944 million US dollars, the change to the electricity cost per kWh is insignificant due to the huge base size. However, if an electricity price commission is given to solar electricity either by the government offset or by a forced higher buying price from the utility, the price of the electricity only needs to be increased to US$0.133/kWh to make such a PV system profitable. To make the system economically viable, it has been found that an electricity price of US$0.158/kWh is required. If carbon trading is also considered which can be used to offset part of the cost, there needs a US$7/ton on top of the current carbon trading price in the EU to make the system profitable, which is foreseeable in the near future based on the current price trend.

From the economic analysis on different XEV models, it is found that at current stage, strong government incentives are necessary to implement XEV system. However, the government seems quite lukewarm about the XEVs. This is most likely because that there is no car and battery industry in Singapore. Heavy investment in XEV system does not necessarily stimulate the economy much. In addition, as an Annex-B country in Kyoto Protocol, the pressure on CO2 reduction is not desperately urgent for Singapore. In addition, the relatively small reduction of CO2 by implementing XEV systems does not provide enough driving force for the country to adopt green vehicles on a large scale. After all, promoting public transport offers another economical alternative for the government. From the Tie-to-Grid model, it is also found that solar PV electricity is still not cost competitive with the current utility price at its present stage of technical development.

While a few trial sites have been built to test the feasibility of roof-top PV in Singapore, it is believed that Singapore is still waiting for PV price to further drop down before a large scale deployment. Air-conditioning seems a good usage for this renewable energy, before the XEV systems are implemented.

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Appendix A

Nanoparticle $LiCoO_2$ Cathode Power and Energy Densities Calculation

The calculation is based on $LiCoO_2$ battery experimental data by Cho et al[28] shown in the figure below.

Maximum capacity is 165mAh/g/

At C/10 rate, discharge current=$\frac{165\text{mAh}}{\text{g}} \times 0.1 = 16.5\text{mA/g}$

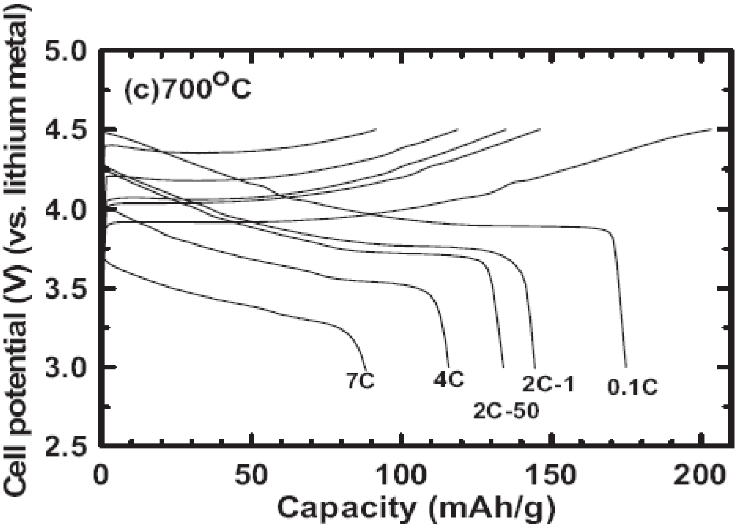
Average discharge voltage=4.1V, with capacity of 165mAh/g.

Energy density=$\frac{165\text{mAh}}{\text{g}} \times 4.1\text{V} = 676.5\text{Wh/kg}$

Power density=$\frac{\text{Energy density}}{\text{Time}} = \frac{676.5\text{Wh/kg}}{10\text{h}} = 67.65\text{W/kg}$

Similarly, the rest of power and energy densities are able to be estimated at various discharge rates.

Discharge C-rate	Current (mA/g)	Voltage (V)	Capacity (mAh/g)	Power density (W/kg)	Energy density (Wh/kg)
C/10	16.5	4.1	165	67.65	676.5
2C	260	3.9	140	1092	546
4C	440	3.75	110	1760	440
7C	560	3.5	80	1960	280



Metal Cation Substituted $LiMn_2O_4$ Cathode Power and Energy Densities Calculation

The calculation is based on $LiMn_{1.9}Ni_{0.1}O_4$ experimental data by Shin et al[47].shown in the figure below.

Maximum capacity is 120mAh/g/

At C/10 rate, discharge current=$\frac{120\text{mAh}}{\text{g}} \times 0.1 = 12\text{mA/g}$

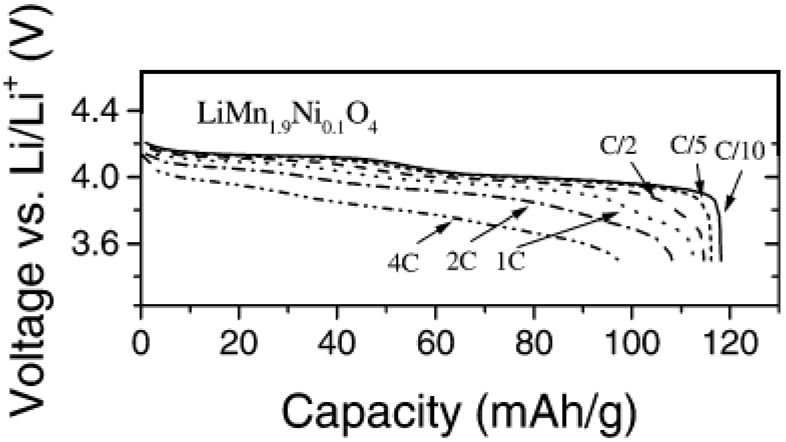
Average discharge voltage=4V, with capacity of 120mAh/g.

Energy density=$\frac{120\text{mAh}}{\text{g}} \times 4\text{V} = 480\text{Wh/kg}$

Power density=$\frac{Energy\ density}{Time} = \frac{480Wh/kg}{10h} = 48W/kg$

Similarly, the rest of power and energy densities are able to be estimated at various discharge rates.

Discharge C-rate	Current (mA/g)	Voltage (V)	Capacity (mAh/g)	Power density (W/kg)	Energy density (Wh/kg)
C/10	12	4	120	48	480
C/5	24	4	115	92	460
C/2	60	3.9	110	214.5	429
C	120	3.9	100	390	390
2C	240	3.8	100	760	380
4C	480	3.7	90	1332	333



Doped $LiFePO_4$ Cathode Power and Energy Densities Calculation

The calculation is based on the experimental data by professor Chiang's group[13] shown in the figure below.

Maximum capacity is 150mAh/g.

At C/10 rate, discharge current=$\frac{150mAh}{g} \times 0.1 = 15mA/g$

Average discharge voltage=3.5V, with capacity of 150mAh/g.

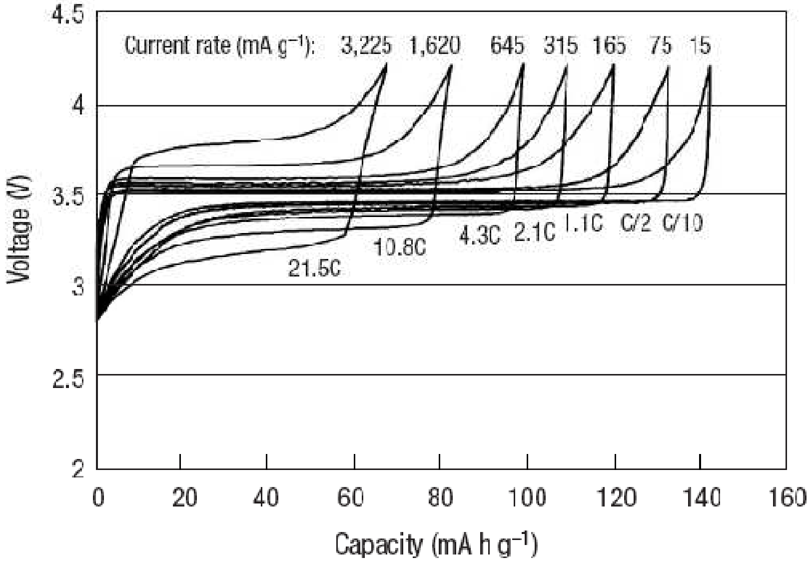
Energy density=$\frac{150mAh}{g} \times 3.5V = 525Wh/kg$

Power density=$\frac{Energy\ density}{Time} = \frac{525Wh/kg}{10h} = 52.5W/kg$

Similarly, the rest of power and energy densities are able to be estimated at various discharge rates.

Discharge C-rate	Current (mA/g)	Voltage (V)	Capacity (mAh/g)	Power density (W/kg)	Energy density (Wh/kg)

C/10	15	3.5	150	52.5	525
C/2	75	3.5	130	227.5	455
1C	150	3.5	120	414	414
2C	300	3.4	110	748	374
4C	600	3.3	100	1320	330
10C	1500	3.25	85	2762	276
20C	3000	3.2	65	4160	208



$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ Cathode Power and Energy Densities

The calculation is based on the experimental data by Yabuuchi et al[66] shown in the figure below.

From what they report

Maximum capacity is 200mAh/g.

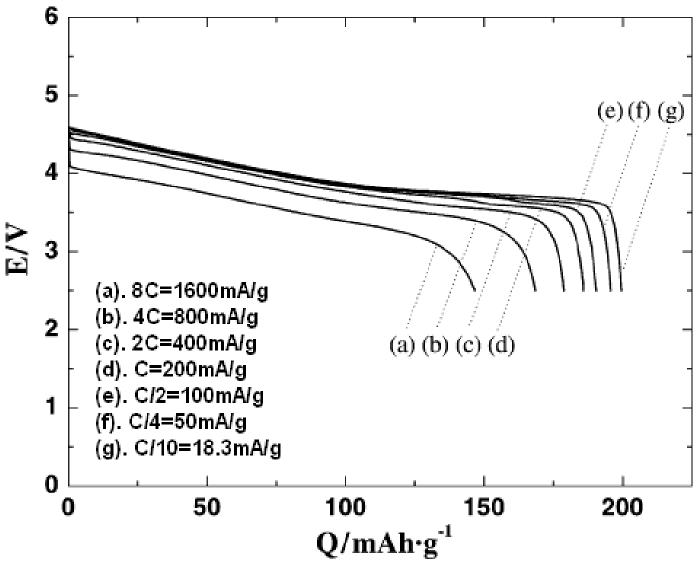
At C/10 rate, discharge current=18.3mA/g≅0.1C

Average discharge voltage=4.25V

Energy density=$\frac{200mAh}{g} \times 4.25V = 850Wh/kg$

Power density=$\frac{Energy\ density}{Time} = \frac{850Wh/kg}{10h} = 85W/kg$

Similarly, the rest of power and energy densities are able to be estimated at various discharge rates.



Discharge C-rate	Current (mA/g)	Voltage (V)	Capacity (mAh/g)	Power density (W/kg)	Energy density (Wh/kg)
C/10	18.3	4.25	200	85	850
C/4	50	4.25	190	202	808
C/2	100	4.1	175	359	718
C	200	4	170	680	680
2C	400	4	160	1280	640
4C	800	3.8	150	2280	570
8C	1600	3.5	125	3500	438

Appendix B
Future electric vehicle models

Automaker	Battery type	Model	Type	Launch date
Toyota	Li-ion	Mini Van	HEV	2010
	Li-ion	Lexus 600h	HEV	2012
	Li-ion	Prius III	HEV	2013
	Li-ion	Sedan	PHEV	2009
	Li-ion	N.A.	BEV	2013
Hino	NiMH	N.A.	HEV	N.A.
Ford	Li-ion	Escape	HEV	2012
	Li-ion	Edge(SUV)	HEV	2013
	Li-ion	Fusion	HEV	2013
Mercury(Ford)	Li-ion	Mariner(SUV)	HEV	2012
	N.A.	Milan	HEV	2013
Lincoln	N.A.	MKZ	HEV	2013
Volkswagen	Li-ion	Toualeg(SUV)	HEV	2011
	Li-ion	Golf Touran	HEV	2012
	N.A.	Golf Twin Drive	PHEV	N.A.
Porsche	N.A.	Cayenne	HEV	2011
Audi	N.A.	A7	HEV	2011
Tesla	Li-ion	Roadster	PHEV	2011
	Li-ion	Sedan	N.A.	2011
Daimler	Li-ion	Smart ED	PHEV	2011
Honda	NiMH	Civic	HEV	2010
Nissan	Li-ion	Sedan(FR)	HEV	2010
	NCM	X-Trail(SUV)	HEV	2012
	N.A.	Sedan	HEV	2012
	N.A.	N.A.	HEV	2015
	N.A.	Sedan	PHEV	2015
	N.A.	Compact Sedan	BEV	2010
	N.A.	N.A.	BEV	2015
Suzuki	N.A.	N.A.	BEV	N.A.
Subaru	N.A.	Compact Sedan	BEV	2009
Honda	Li-ion	Civic	HEV	2011
	Li-ion	Insight	HEV	2012
	N.A.	CR-Z	HEV	2012
	N.A.	FIT	HEV	2015

	N.A.	N.A.	HEV	2015
Mitsubishi	N.A.	iMiEV	BEV	2009
PSA(Peugeot)	N.A.	N.A.	BEV	2012
GM	Li-ion	Volt	PHEV	2010
	Li-ion	Tahoe, Yukon	HEV	2012
	Li-ion	Escalade	HEV	2012
	Li-ion	Sierra	HEV	2012
	Li-ion	Silverado	HEV	2012
	Li-ion	N.A.	HEV	2015
BMW	N.A.	3-Series	HEV	2012
	N.A.	5-Series	HEV	2012
Chrysler	N.A.	Chrysler EV	PHEV	2013
	N.A.	Jeep	PHEV	2013
	N.A.	Dodge EV	BEV	2011
Think	Li-ion	City	BEV	2010
BYD Auto	Li-ion	F3DM	PHEV	2009
	Li-ion	F3e	BEV	2009

Appendix C

Material cost

For a 425Wh high energy cell, amount of $LiFePO_4$ cathode material used in one cell can be estimated as: $\frac{425Wh}{525Wh/kg} = 810g$. Bottom-up approach has been used to calculate the total material cost per cell.

Material cost of a 425Wh $LiFePO_4$ cell

$LiFePO_4$ battery			
Material	Price($/kg)	Quantity(kg)	Cost/Cell($)
Cathode	$28	0.81	$22.68
Anode(Graphite)	$20	0.32409	$6.482
Electrolyte	$40	0.618	$24.72
Separator	$150	0.0605	$9.075
Can and Vent		0.291	$3.2
Binder	$45	0.093501	$4.208
Copper	$15	0.087348	$1.310
Aluminum	$20	0.036228	$0.725
Carbon	$20	0.026682	$0.534
Other	$20	0.0671	$1.342
Total		2.41445	$74.275

Similarly, material cost per cell for $LiCoO_2$, $LiMn_2O_4$, and $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ batteries can be estimated as shown in table below.

$LiCoO_2$ battery			
Material	Price($/kg)	Quantity(kg)	Cost/Cell($)
Cathode	50	0.63	31.5
Anode(Graphite)	20	0.2520716	5.041431208
Electrolyte	40	0.618	24.72
Separator	150	0.0605	9.075
Can and Vent		0.291	3.2
Binder	45	0.0727233	3.27254721
Copper	15	0.0679377	1.019065029
Aluminum	20	0.0281769	0.563538265
Carbon	20	0.0207525	0.415050405
Other	20	0.0671	1.342
Total		2.1082619	80.14863212

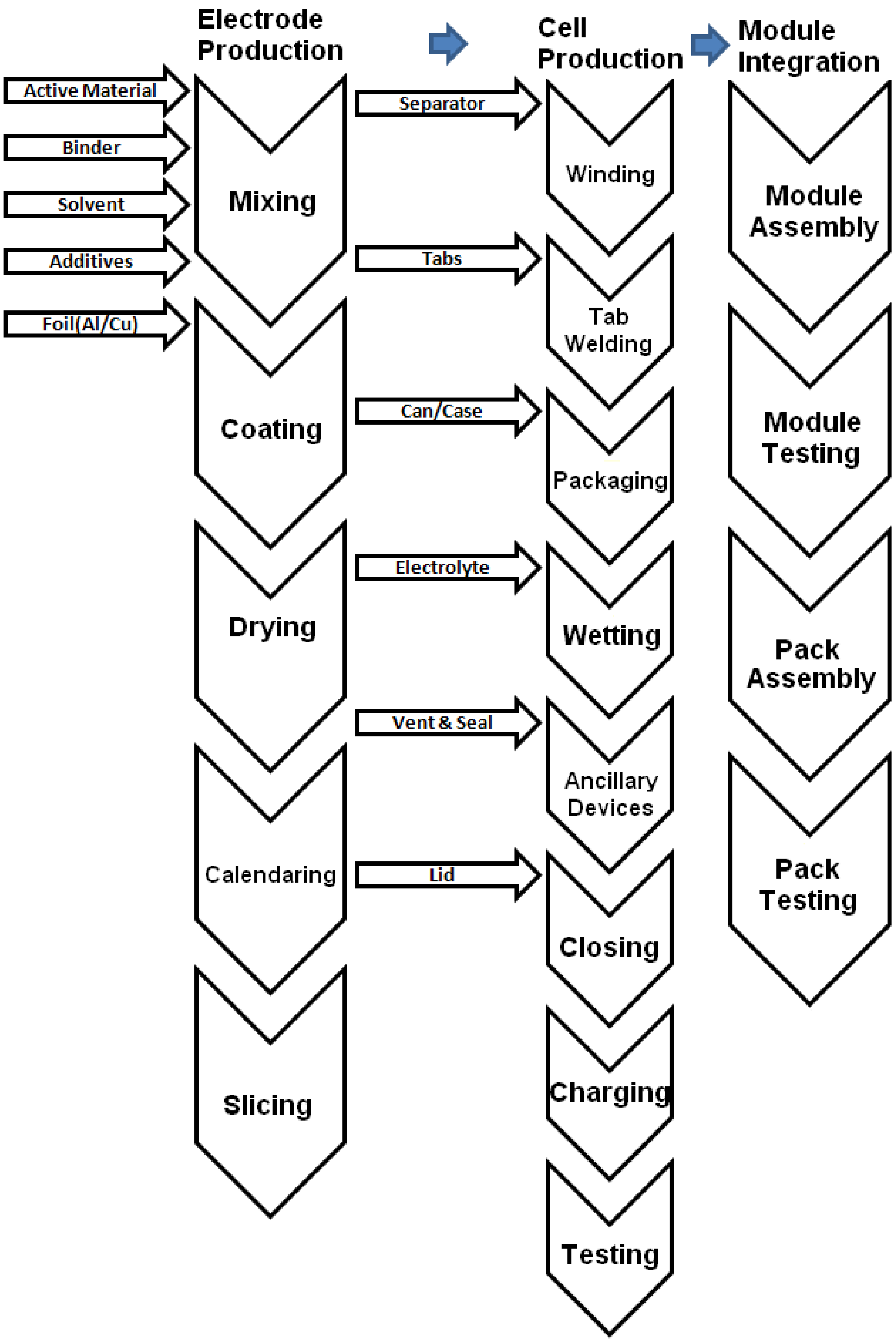
$LiMn_2O_4$ battery			
Material	Price($/kg)	Quantity(kg)	Cost/Cell($)

Cathode	28	0.89	24.92
Anode(Graphite)	20	0.356101	7.122021866
Electrolyte	40	0.618	24.72
Separator	150	0.0605	9.075
Can and Vent		0.291	3.2
Binder	45	0.102736	4.623122249
Copper	15	0.095975	1.439631549
Aluminum	20	0.039805	0.796109612
Carbon	20	0.029317	0.586341048
Other	20	0.0671	1.342
Total		2.550535	77.82422632

$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$			
Material	Price($/kg)	Quantity(kg)	Cost/Cell($)
Cathode	50	0.5	25
Anode(Graphite)	20	0.200057	4.001136
Electrolyte	40	0.618	24.72
Separator	150	0.0605	9.075
Can and Vent		0.291	3.2
Binder	45	0.057717	2.59726
Copper	15	0.053919	0.808782
Aluminum	20	0.022363	0.447253
Carbon	20	0.01647	0.329405
Other	20	0.0671	1.342
Total		1.887125	71.52084

Appendix D

Battery manufacturing flow



Appendix E
Manufacturing Cost

Manufacturing Equipment and Labor Force for One Production Line

Equipment	Price	No. of labor
Mixing Machine	$100,000	5
Coating Machine	$80,000	5
Calendaring Machine	$50,000	2
Slitting Machine	$50,000	1
Cutting Machine	$50,000	1
Winding Machine	$50,000	2
Tab Welding Machine	$50,000	2
Automated Assembly Machine	$100,000	3
Testing	$50,000	6
Packaging	$50,000	4
Total	$630,000.00	31

Following table shows a cost break down of four types of Li-ion batteries. A 5% material cost discount is assumed.

$LiFePO_4$	
Capacity (cells)	3000000
Cell material cost ($/cell)	$70
Variable cost	
Material cost	$210,000,000.00
Labor cost (2 shifts)	$32,140,800.00
Electricity cost	$72,648.00
Yield adjustment	$11,052,631.58
Total variable cost	$255,002,921.68
Machine cost	$3,780,000.00
Building cost	$6,000,000.00
Machine amortization cost	$443,997.38
Building amortization cost	$605,155.04
Annual interest rate	10%
Machine life time	20
Building life time	50
Total amortization cost	$1,049,152.43
Overhead cost	$21,000,000.00
Total fix cost	$22,049,152.43
Total annual cost	$275,315,232.00
Cell cost	$91.77

LiCoO2	
Capacity(cells)	3000000
Cell material cost($/cell)	76.133
Material cost($)	$228,399,000.00
Labor cost (2 shifts)	$32,140,800.00
Electricity cost($)	$72,648.00
Yield adjustment	$12,021,000.00
Total variable cost	$272,633,448.00
Fix cost	
Machine cost($)	$3,780,000.00
Building cost($)	$6,000,000.00
Machine amortization cost	$443,997.38
Building amortization cost	$605,155.04
Annual interest rate	10%
Machine life time	20
Building life time	50
Total amortization cost	$1,049,152.43
Overhead cost	$21,000,000.00
Total fix cost	$22,049,152.43

LiMn2O4	
Capacity(cells)	3000000
Cell material cost($/cell)	74
Material cost($)	$222,000,000.00
Labor cost (2 shifts)	$32,140,800.00
Electricity cost($)	$72,648.00
Yield adjustment	$11,684,210.53
Total variable cost	$265,897,658.53
Fix cost	
Machine cost($)	$3,780,000.00
Building cost($)	$6,000,000.00
Machine amortization cost	$443,997.38
Building amortization cost	$605,155.04
Annual interest rate	10%
Machine life time	20
Building life time	50
Total amortization cost	$1,049,152.43
Overhead cost	$21,000,000.00

Total fix cost	$22,049,152.43

NCM	
Capacity(cells)	3000000
Cell material cost($/cell)	$68.40
Material cost($)	$205,200,000.00
Labor cost (2 shifts)	$32,140,800.00
Electricity cost($)	$72,648.00
Yield adjustment	$10,800,000.00
Total variable cost	$248,213,448.00
Fix cost	
Machine cost($)	$3,780,000.00
Building cost($)	$6,000,000.00
Machine amortization cost	$443,997.38
Building amortization cost	$605,155.04
Annual interest rate	10%
Machine life time	20
Building life time	50
Total amortization cost	$1,049,152.43
Overhead cost	$21,000,000.00
Total fix cost	$22,049,152.43

Appendix F

$LiCoO_2$ battery Cycle Performance

For Al_2O_3 coated $LiCoO_2$ battery, Figure 5 demonstrates that it retains 160mAh/g capacity after 70 cycles of operation at C/2 discharge rate. Hence the capacity loss is estimated as:

$$\frac{175mAh/g - 160mAh/g}{175mAh/g \times 70} = 0.1224\%\ per\ cycle$$

Hence, after 500 cycles of operation, there will be only 38.78% of its initial capacity remained.

$LiMn_2O_4$ battery Cycle Performance

Similar approach can be used to assess durability for a nickel substituted $LiMn_2O_4$ battery. Result from

Figure 8 shows that after 200 cycles of operation at C rate, 95% of battery's initial capacity is retained. Hence, with capacity loss 0.025% per cycle, after 2300 cycles of operation, 43% of its initial capacity will remain. 75% capacity retention is achieved after 1000 cycles of operation.

Doped $LiFePO_4$ battery

Figure 12 shows that $LiFePO_4$ battery has a capacity loss of 0.005% per cycle discharge at C rate. After 2300 cycles of operation, 89% of initial capacity will remain.

$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ battery

Figure 13 shows that $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ battery has two cycling performance regions. Under low operation voltage it is estimated that only 25% of the initial capacity is remained after 500 cycles of operation at C/20 discharge rate. Under high operation voltage, the battery suffers severe capacity fading where only 37.5% of its initial capacity is retained after 50 cycles of operation at C/20 discharge rate.

Appendix G

PHEV Li-ion battery pack cost

In order to meet both power and energy requirements for PHEV battery pack, 414W/kg and 414Wh/kg power and energy densities will be used to calculate an optimum numbers of $LiFePO_4$ cells in a 40-mile PHEV.

$$\frac{11.6kWh}{0.81kg \times 414Wh/kg} = 35\ cells$$

Same method is applied for other Li-ion batteries with oversized battery pack.

BEV Li-ion battery pack cost

Similarly, 227.5W/kg and 455Wh/kg power and energy densities will be used for $LiFePO_4$ battery in a BEV. Hence, the number of $LiFePO_4$ cells used in BEV can be calculated as:

$$\frac{30kWh}{455Wh/kg \times 0.81kg} = 81cells$$

Same method is applied for other Li-ion batteries.

Following table summarizes the number cells used after over sizing in both 40-mile PHEV and BEV:

Battery type	Number of cells in 40-mile PHEV	Number of cells in BEV
$LiCoO_2$	47	121
$LiMn_2O_4$	40	79
$LiFePO_4$	35	81
$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$	43	105

Appendix H
Battery Utility Analysis

Multi-attribute utility for Li-ion battery in 40-mile PHEV

Attribute	Cost ($/kWh)	Durability (2300 cycles)	Energy Density (Wh/kg)
Point1	150.00	30.00%	50.00
Point2	320.00	55.00%	80.00
Point3	490.00	70.00%	110.00
Point4	660.00	85.00%	140.00
Point5	830.00	100.00%	170.00
Point6	1000.00		200.00
Utility	Cost	Durability	Energy Density
Point1	1.000	0.000	0.000
Point2	0.815	0.230	0.410
Point3	0.530	0.630	0.610
Point4	0.260	0.800	0.725
Point5	0.125	1.000	0.925
Point6	0.000		1.000
LMO battery attribute	625	42.5%	123
LMO battery single utility	0.2758	0.038	0.6598
multi-attribute utility	0.59		

Multi-attribute utility for Li-ion battery in BEV

Attribute	Cost ($/kWh)	Durability (2300 cycles)	Energy Density (Wh/kg)
Point1	50.00	40.00%	50.00
Point2	240.00	55.00%	120.00
Point3	430.00	70.00%	190.00
Point4	620.00	85.00%	260.00
Point5	810.00	100.00%	330.00
Point6	1000.00		400.00
Utility	Cost	Durability	Energy Density
Point1	1.000	0.000	0.000
Point2	0.815	0.230	0.410
Point3	0.530	0.630	0.610
Point4	0.260	0.800	0.725
Point5	0.125	1.000	0.925
Point6	0.000		1.000
LMO battery attribute	625	75%	128.7
LMO battery single utility	0.2386	0.69	0.4348
Multi-attribute utility	0.5999		

Appendix I

PHEV Battery Cost

The number of cells used in PHEV will be:

$$\frac{8.8kWh}{0.81kg \times 414wh/kg} = 27cells$$

Oversized battery pack will have $\frac{27cells}{0.7} = 39cells$

Battery pack cost: $39cells \times \frac{\$213}{cell} = \$8307$

BEV Battery Cost

The number of cells used in BEV will be:

$$\frac{22kWh}{0.81kg \times 455Wh/kg} = 60cells$$

Oversized battery pack will have $\frac{60cells}{0.7} = 86cells$

Battery pack cost: $86cells \times \frac{\$213}{cell} = \$18318$

Example of NPV of all electric vehicles compared with gasoline counterpart.

Daily mileage (mile)	50
Electricity price ($/kWh)	$0.07
Gasoline price ($/gallon)	$2.56
Gasoline car	
Fuel efficiency (mpg)	26
OMV	$22,325.00
Vehicle exercise tax	$558.00
Gasoline car total cost	$22,883.00
Gasoline car daily operation cost	$4.92
HEV	
Fuel efficiency (mpg)	30
OMV	$25,555.00
Vehicle exercise tax	$639.00
HEV total cost	$26,194.00
HEV tax rebate	$1,550.00
HEV premium cost	$1,761.00
HEV daily operation cost	$4.27
HEV annual saving	$237.25

HEV NPV	$307.73
PHEV	
CS mode fuel efficiency (mpg)	50
OMV	$38,307.00
Vehicle exercise tax	$957.00
PHEV total cost	$39,264.00
PHEV tax rebate	$7,500.00
PHEV premium cost	$8,881.00
PHEV daily operation cost	$1.13
PHEV annual saving	$1,383.35
PHEV NPV	$3,147.48
BEV	
OMV	$43,318.00
Vehicle exercise tax	$1,082.00
BEV total cost	$44,400.00
BEV tax rebate	$13,000.00
BEV premium cost	$8,517.00
BEV daily operation cost	$0.77
BEV annual saving	$1,514.75
BEV NPV	$4,624.57