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Evaluation of Electric Vehicle Power Technologies

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***Abstract*--The evolution in power technologies from combustion engine to hybrid or pure electricity requires automakers to mobilize organizational capability as well as to change operational patterns. Conventional combustion engine, hybrid, plug-in hybrid, and pure electric vehicles of various engineering designs are among the competing technological alternatives for the future. Given the situation, firms with heavy R&D investments in renewable vehicle energy face the dilemma to choose among these competing technologies. This research develops a technology evaluation model which incorporates technological factors and market criteria to facilitate decision making on allocating resources to various renewable power technologies for passenger vehicles. Using analytic hierarchy process (AHP), the technology evaluation model was quantified by experts in Lithium-Ion batteries, Fuel Cell, Hybrid technologies as well as by consumer survey. Expert quantification ranks the technological alternatives in order of technological performances while consumer survey prioritizes user needs for the technological performances. The research should be able to help automakers and technological developers of electrical power effectively mobilize resources and deploy strategies for the future.**

I. INTRODUCTION

Increasing environmental concerns and depleting fossil energy have called for R&D investments on technologies for renewable energy vehicles [1]. For automakers, strategic move from incumbent combustion engine technology to either hybrid or pure electric power requires to mobilize organizational capability as well as to change business operation [2]. In addition to shift in technological paradigm, lack of consumer incentive to adopt vehicles powered by renewable energy pose challenges to incumbent automakers and technology suppliers [3]. Under these circumstances, conventional combustion engine, hybrid, plug-in hybrid, and pure electric vehicles of various engineering designs are among the competing technological paradigms for the future [4]. Given all these conditions, major automakers face the dilemma to choose among these competing technologies.

Although hybrid and pure electric cars have been commercialized, adoption of these technologies by mainstream market is unforeseeable. Will electric car dominate the future market or just a niche, such as commuting cars [5]? If it will prevail, what will be the most accepted power technologies? Answers to these questions certainly help management positioning the firm to win the technological campaign and preempt future market. This research aims to develop a technology evaluation model which incorporates technological factors and market criteria to facilitate allocating resources to various renewable power technologies for vehicles. The research should be able to help automakers and suppliers of electric power technology effectively mobilize resources and deploy strategies for future technological shift.

II. LITERATURE REVIEW

Presently most hybrid or pure electric vehicles are equipped with Lithium-Ion (Li-Ion) batteries because of high energy density and convenient rechargeable characteristic [6]. Along with Li-Ion rechargeable batteries, major automakers have also invested in fuel cell technologies as an alternative [7]. Another alternative is plug-in hybrid, a combination of conventional combustion engine and battery power, vehicles [1].

A. Li-Ion technology

Li-Ion battery technology has been developing along with the growth of consumer electronics market. While hybrid vehicles rely on recycling excessive power generated by combustion engine or during brakes, pure Li-Ion battery cars require recharging technologies and facilities such as vehicle-to-grid (V2G) [8]. In addition to electricity grids, Li-Ion battery storages suffer from degradation that requires further technological development [6]. Also required is intelligent system to manage vehicle flow and avoid energy outage during peak load [9]. Application of information and communication technologies to plug-in vehicles will possibly improve the utilization of renewable energy by optimizing the supply and demand [10]. In general, Li-Ion battery has been used in hybrid, plug-in hybrid, and pure electric vehicles with recharging, driving range, cost [11], and other technological or infrastructural barriers to mass market adoption.

B. Fuel cell technology

While Li-Ion battery has commercialized in hybrid and pure electric cars, major automakers, including Toyota, Honda, and Daimler do not overlook fuel cell as a critical substitute for Li-Ion battery [7]. However, application of fuel cell technology to electric vehicles requires careful strategic analysis on technologies, markets, and policies [12]. Iceland's multiple projects on hydrogen fuel cell for public transportation system demonstrated a viable process for utilizing the technology [13]. As the power grid to Li-Ion technology, refuel stations are the infrastructure for fuel cell technology. Daimler, Honda, and Toyota have been investing in fuel cell vehicles and accumulating technological patents [7]. Although fuel cell encompasses a variety of types, such as Proton-Exchange Membrane Fuel Cell (PEMFC), Direct Methanol Fuel Cell (DMFC), and so on, a recent research forecasts that R&D in fuel cell technologies will peak and mature in year 2018 [14]. The research also reports that excessive cost and material limitations are major barriers to mass application of fuel cell technologies.

C. Technological Criteria for Electric Vehicle

The adoption of electric vehicle by mass market can be examined by classic innovation diffusion theories. Rogers' innovation diffusion theory proposes that relative advantage, compatibility, complexity, trialability, and observability are the factors influencing rate of adoption [15]. In addition to the influencing factors, various types of consumers play roles in the diffusion process. Innovation adopters can be divided into categories with degrees of enthusiasm in the innovation. Among the adopter categories, early majority, regarded as the critical mass, is decisive to the successful diffusion of innovation. Consumers of commute and errand are recognized as the two major segments in the US electric vehicle market [5]. Despite the needs for different market segments may vary, operation costs, including fuel, tax, maintenance expenses and purchase price probably are the common concern to consumers [16]. Daziano and Chiew [17] conducted a consumer survey and found that purchasing price, operating costs, driving range, recharging time, refueling network density, power, emission, and incentives for adoption were the major factors influencing the diffusion of electric vehicles. Egbue and Long [18] investigated the barriers to electric vehicle adoption, and reported that battery range, cost, charging infrastructure, reliability and safety were the major concerns to consumers. A survey using social preferences for price, range, performance, environment, durability, and convenience as the criteria on German market to identify potential buyers [19]. In the study, although price was the major concern, priorities of the social preferences vary among potential buyer groups. Taking all the concerns into consideration, this research uses a multiple criteria evaluation model to incorporate all influencing factors. In addition to technological factors, social needs of different market segments are also incorporated in the model for the segmentation and positioning purposes in the emerging electric vehicle market.

III. METHOD

A. Research Design

Given the need to make decision on the technological alternatives with multiple criteria, a multiple criteria decision model (MCDM) is created. Additionally, consumer weighting on each decision criterion may vary with market segments. Taken these factors into consideration, this study employed the analytic hierarchy process (AHP)[20] which incorporates a decision hierarchy of three levels, namely overall benefit, technological characteristics, and technological alternatives. At the overall benefit level, luxury and economic passenger cars are two separate market segments. Technological evaluation criteria are incorporated at the technological characteristics level. For the technological alternatives, the Li-Ion, Fuel cell, and hybrid are the technologies to be evaluated. The AHP model is depicted in the figure 1.

B. Evaluation Criteria

Under the overall benefits for luxury and economic passenger car markets are the decision criteria used to evaluate technological characteristics of available technological alternatives. The evaluation criteria are taken from existing researches that are reviewed and discussed in the literature review section. These criteria are also validated by technological experts of electric vehicle. Following are the operational definitions of the evaluation criteria.

- Purchasing cost: the price of the vehicle.
- Operating cost: the cost of fuel and maintenance.
- Safety: the avoidance of hazard conditions caused by power system.
- Driving range: traveling distance with a full capacity of fuel.
- Refuel facility: availability of refuel facility.
- Refuel time: duration required for a full capacity refuel.
- Battery life: durability of the power system
- Power: energy per unit time provided by the power system
- Environment: reduction amount of exhaust of the power system.

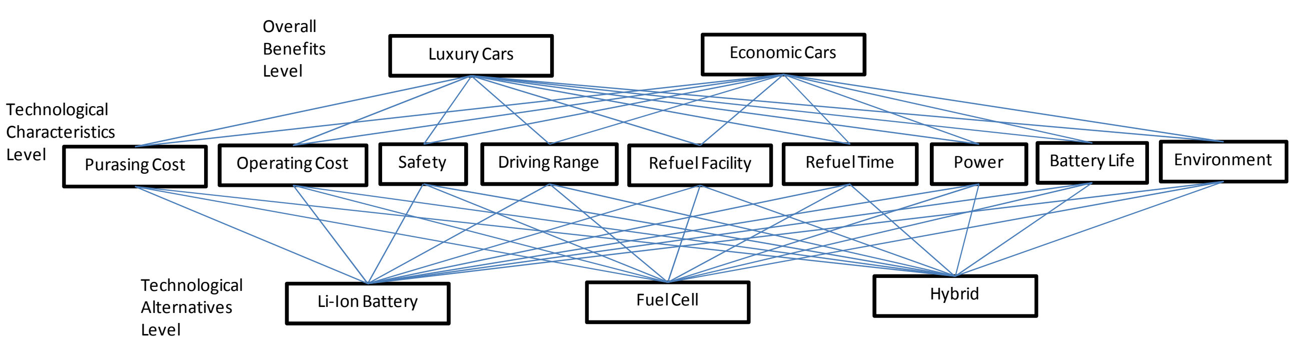

Fig. 1 The Analytic Hierarchy Model

C. Subjects and Scales for Judgment Quantification

The AHP model was quantified by experts and consumers. The experts evaluated technological alternatives over the criteria using pairwise comparison method with 1-9 scale. The Expert Choice software was employed to process expert judgments. With 3 technological alternatives and 9 evaluation criteria, the analysis generated a 3 by 9 matrix of Eigen values.

Consumers were divided into luxury and economic segments based on the vehicle types under their ownership. Questionnaire used for consumer survey adopted Likert 1-9 scale for the evaluation of the importance of each technological criterion to overall benefit. Consumer profile data were also collected for market analysis purpose. The SPSS software was employed to conduct consumer data analyses. Descriptive statistics including consumer weightings on the technological criteria for luxury, economic, and all markets were reported. Analyses on consumer weightings generated three 9 by 1 vectors which were synthesized with the expert matrix to generate the overall benefits of the tree technological alternatives. The matrix operation is elaborated by the following equation.

$$B_i = \sum_{i=1}^{3} \sum_{j=1}^{9} [T_{ij} \times C_j] \qquad (1)$$

Where:

B_i= The overall benefit of *i*th technological alternative for consumers

T_{ij}= The contribution of *i*th technological alternative to *j*th technological characteristics.

C_j=The consumer weights on *j*th technological characteristics.

The ANOVA technique was conducted to further explore differences between luxury and economic passenger car consumers. Statistical significance of consumer weightings on the 9 technological criteria between luxury and economic market segments are reported.

IV. RESULTS

Four experts completed the judgment quantification questionnaire. The experts are senior engineers and technological managers in battery material and electrical vehicle research areas. All of them have more than 20 years' experience in the fields. The four experts' judgments of technological alternatives on technological characteristics are combined and listed in Table 1.

The results show that except environment consideration and operating cost, current hybrid technology has advantages in the remaining factors over Li-Ion and Fuel Cell technologies. Li-Ion technology has advantage of operating cost over Fuel Cell and Hybrid. To further compare the two pure EV technologies, the hybrid was removed from the analysis, and the results are shown in Table 2.

The results show that Li-Ion technology has the advantages of purchasing cost, operating cost, refuel facility while Fuel Cell performs better than Li-Ion in driving range, battery life, and refuel time. These results suggest that the two technologies although competing with each other, they may also complementary to each other.

The survey sample consists of 54 respondents, in which 50 are free from missing data and used for analyses. Among the 50 complete respondents, 14 are luxury car owners and 36 are economic car owners. The averages of consumer weightings on each technological characteristic are summarized in Table 3. The two market segments, luxury and economic, were analyzed individually and collectively.

From consumer view, environment is the first concern followed by safety. Driving range, battery life, and refuel facility are the next important factors to consumers. Further analysis on the difference between luxury and economic market, the ANOVA results are reported in Table 4.

TABLE 1. COMBINATIONS OF EXPERT JUDGMENTS ON 3 TECHNOLOGICAL ALTERNATIVES

	PurCost	OprCost	Safety	DRange	Refuel	Blife	Power	RFTime	Environ
Li-Ion	0.277	**0.549**	0.150	0.070	0.134	0.078	0.192	0.068	**0.476**
Fcell	0.066	0.111	0.122	0.226	0.074	0.173	0.161	0.224	**0.441**
Hybrid	**0.658**	0.340	**0.728**	**0.704**	**0.792**	**0.749**	**0.647**	**0.707**	0.083

TABLE 2. COMBINATIONS OF EXPERT JUDGMENTS ON 2 TECHNOLOGICAL ALTERNATIVES

	PurCost	OprCost	Safety	DRange	Refuel	Blife	Power	RFTime	Environ
Li-Ion	**0.833**	**0.845**	0.568	0.205	**0.709**	0.250	0.599	0.185	0.532
Fcell	0.167	0.155	0.432	**0.795**	0.291	**0.750**	0.401	**0.815**	0.468

TABLE 3. CONSUMER WEIGHTINGS ON TECHNOLOGICAL CHARACTERISTICS

Market Segments	PurCost	OprCost	Safety	DRange	Refuel	Blife	Power	RFTime	Environ
Luxury	7.56	7.56	8.19	8.00	7.81	7.75	7.69	7.88	8.44
Economic	7.38	7.44	8.03	7.65	7.56	7.62	7.21	7.32	8.03
All	7.44	7.48	8.08	7.76	7.65	7.66	7.36	7.50	8.16

TABLE 4. ANOVA ON THE LUXURY AND ECONOMIC CAR MARKET SEGMENTS

		Sum of Squares	df	Mean Square	F	Sig.
Purchasing Cost	Between Groups	.353	1	.353	.314	.578
	Within Groups	53.967	48	1.124		
	Total	54.320	49			
Operating Cost	Between Groups	.160	1	.160	.212	.648
	Within Groups	36.320	48	.757		
	Total	36.480	49			
Safety	Between Groups	.272	1	.272	.610	.439
	Within Groups	21.408	48	.446		
	Total	21.680	49			
Driving Range	Between Groups	1.355	1	1.355	2.048	.159
	Within Groups	31.765	48	.662		
	Total	33.120	49			
Refuel Facility	Between Groups	.667	1	.667	1.165	.286
	Within Groups	26.313	46	.572		
	Total	26.979	47			
Battery Life	Between Groups	.191	1	.191	.315	.577
	Within Groups	29.029	48	.605		
	Total	29.220	49			
Power	Between Groups	2.524	1	2.524	3.274	.077
	Within Groups	36.996	48	.771		
	Total	39.520	49			
Refuel Time	Between Groups	3.309	1	3.309	5.441	.024
	Within Groups	29.191	48	.608		
	Total	32.500	49			
Environment	Between Groups	1.812	1	1.812	5.144	.028
	Within Groups	16.908	48	.352		
	Total	18.720	49			

The analysis results indicate that refuel time and environment concerns significantly different between the two market segments with the p values of 0.024 and 0.028 respectively. For both criteria, the weightings by luxury consumers are greater than those of economic consumers. With the p value of 0.077, power probably is the next significant factor to differentiate the two market segments. Other factors were not weighted differently between the two groups.

The overall benefits of technological alternatives were obtained by synthesizing expert judgments and consumer weightings using matrix operations as depicted in equation 1. The results for the three-technology evaluation and the two-technology evaluation are illustrated in Table 5.

For the three-technology evaluation, hybrid technology has obvious advantages over the other two rivalries in both luxury and economic segments. For the head-to-head comparison of Li-Ion and Fuel Cell technologies, although Li-Ion performs better than Fuel Cell in both market segments, the differences are not substantial.

V. DISCUSSION AND CONCLUSION

This study integrated expert judgments and consumer weightings to advance understanding of technological performance and user needs of future EV technologies. Consumer survey was designed to generate information for the luxury and economic passenger car market segments. The identified differences between the two market segments provide critical information for automakers in positioning and targeting their pure EV market. The novel design approach that collects data from technological experts and consumers in the market was proven effective in integrating technological information with consumer preferences of dissimilar market segments.

TABLE 5. OVERALL BENEFITS OF TECHNOLOGICAL ALTERNATIVES

	3 Alternatives				2 Alternatives		
Overall Benefit	Luxury	Economic	All		Luxury	Economic	All
Li-Ion	0.221713	0.222467	0.222215		0.52215	0.524256	0.523574
Fcell	0.180415	0.179371	0.179709		0.47785	0.475744	0.476426
Hybrid	0.597868	0.598163	0.598075				

From consumer perspective, environment protection is the most important driver of EV adoption. Both Li-Ion and Fuel Cell technologies over perform the hybrid technology in environment protection. Safety is the second important factor for consumers; however both Li-Ion and Fuel Cell technologies were ranked far behind the hybrid technology by the experts. This result implies that automakers should advance either Li-Ion or Fuel Cell technologies for pure EV to guarantee the safety and build consumer confidence in the technologies.

Aside the incumbent hybrid technology, for pure EV the Li-Ion and Fuel Cell technologies were found complementary to each other. A hybrid of Li-Ion and Fuel Cell probably is an option for the future market if the costs of these two technologies can be further reduced. Purchasing costs of these two technologies are relatively disadvantageous to combustion engine hybrid technology. However, with the advent of material technologies and manufacturing processes, chances for cost reduction of these two environment friendly technologies are possible.

VI. LIMITATION AND FUTURE RESEARCH

The research created a multiple criteria model to evaluate emerging power storage technologies for electric cars. The numbers of experts and sample size of consumer survey sample are not adequate to illustrate the model's full capability. With more experts to quantify the technological alternatives and increment of consumer sample, the research will show relatively significant results.

The research results represent current technological frontier of power storage technologies, the Li-Ion battery and the fuel cell. These technologies will advance and further develop for sure. Similarly, consumer preferences obtained by the survey may change over time. To address the evolutionary nature of technological and market changes, technological forecasting techniques can be incorporated to the model. The combination of AHP model with Delphi [21] or scenario [22] techniques is likely to facilitate exploring future technological trends.

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