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A socio-technical analysis of widespread electric vehicle adoption

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A SOCIO-TECHNICAL ANALYSIS OF WIDESPREAD ELECTRIC VEHICLE ADOPTION

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This dissertation has been prepared in the format of the publication option. Three journal articles are presented.

(1) Pages 6 to 38 "Barriers to widespread adoption of electric vehicles: an analysis of consumer attitudes and perceptions" is in the style required by Energy Policy. It has been accepted and published. The citation is Egbue O. and Long S., 2012 "Barriers to Widespread Adoption of Electric Vehicles: An Analysis of Consumer Attitudes and Perceptions." *Energy Policy*, vol. 48, pp. 717–729. DOI: 10.1016/j.enpol.2012.06.009

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The Introduction, Conclusions, and Appendices have been added for purposes normal to dissertation writing.

ABSTRACT

A combination of high fuel costs, concerns about petroleum availability, and environmental issues associated with conventional vehicles powered by fossil fuels are driving interests in electric vehicles (EVs). Large-scale deployment of EVs can play a significant role in addressing some of these problems. In spite of the benefits of EVs, several obstacles need to be overcome before EVs will be widely adopted. This research focuses on two socio-technical issues that affect widespread adoption and sustainability of EVs, consumer attitudes and perceptions, and supply chain risks of raw materials for EV battery technology.

A major barrier is that consumers tend to resist new technologies that are considered unproved, thus, engineering and policy decisions that consider their critical concerns will have a higher level of success. This research identifies potential socio-technical barriers to consumer adoption of EVs and determines if sustainability issues influence consumer decision to purchase an EV. In addition, this study employs statistical analysis to provide valuable insights into preferences and perceptions of technology enthusiasts.

The second part of this research focuses on a supply chain analysis of lithium, which is a major raw material for lithium-ion batteries used in EVs. This research identifies potential issues with the security and supply of lithium for production of lithium-ion batteries. Furthermore, this study develops a supply chain model with which to investigate the technical, geopolitical, and economic factors that influence the supply of lithium through different life cycle stages.

Finally, this research conducts a bibliometric analysis of the EV research and proposes some policy and research actions to advance the technology.

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TABLE OF CONTENTS

Page

PUBLICATION DISSERTATION OPTION……………………………………………iii

ABSTRACT iv

ACKNOWLEDGMENTS v

LIST OF ILLUSTRATIONS ix

LIST OF TABLES x

SECTION

1. INTRODUCTION………………………………………………………………..1

1.1. BACKGROUND .... ………………………...1

1.2. RESEARCH OBJECTIVES 3

1.3. RESEARCH CONTRIBUTION...4

1.4. DISSERTATION OUTLINE 5

PAPER

I. BARRIERS TO WIDESPREAD ADOPTION OF ELECTRIC VEHICLES: AN ANALYSIS OF CONSUMER ATTITUDES AND PERCEPTIONS……………...6

Abstract……..6

1. Introduction 7

2. Background 9

2.1. Electric Vehicle Technology 9

2.2. Consumer Attitudes and Motivation 11

3. Methodology 14

3.1. Survey……… 14

3.2. Statistical Data Analysis...16

4. Results and Discussion 17

4.1. Sample Description...17

4.2. EV Knowledge, Experience and Interest 18

4.3. Concerns about EVs...22

4.4. Battery: Driving Range and Battery Charging 26

4.5. Sustainability of EVs as a Transportation Option 29

4.6. Unaddressed Concerns about Electric Vehicles 32
5. Conclusions and Implications for Transportation Policymakers 33
6. Future Work 35
Acknowledgement.....……………………………………………………………35
References……………..…………….……………………………………………..35
II. CRITICAL ISSUES IN SUPPLY CHAIN OF LITHIUM FOR ELECTRIC VEHICLE BATTERIES……………………………………………………………39
Abstract……………………………………………………………………………39
1. Introduction...40
2. Overview of Lithium and Electric Vehicle Batteries 42
2.1. Lithium 42
2.2. EV Battery Application 45
3. Methodology 46
4. Results 48
4.1. SAM Summary 48
4.2. Lithium Resources and Reserves 51
4.3. Supply and Demand 53
4.4. Impact of Lithium price on Electric Vehicle Battery Cost........................57
4.5. Geopolitical Environment and Trade Partnering......................................57
4.6. Recycling...61
5. Lithium Supply Chain Framework 62
6. Implications and Conclusion 65
Acknowledgement.......…….……………..………………………………………68
References...……..…...……………………………………………………………...68
III. A BIBLIOMETRIC ANALYSIS OF ELECTRIC VEHICLE RESEARCH: EVALUATING THE TECHNOLOGY AND THE ROLE OF POLICY………...74
Abstract……...74
1. Introduction 75
2. Methods..77
3. Results and Discussion 78
3.1. Trends of publication output. 78

3.2. Distribution by country and affiliation..80
3.3. Distribution by journals..83
3.4. Distribution by subject category and keywords.......................................84
3.5. Most cited works in EV research...86
4. Policy and Research Recommendations...88
5. Conclusions 91
6. Future work..92
Acknowledgement……………………………………………………………92
References…...…………..…………………………………………………...92
SECTION
2. CONCLUSIONS…………………………………………………………..97
APPENDICES
A. ELECTRIC VEHICLE CONSUMER SURVEY...……..………………………...100
B. 10-YEAR VEHICLE COST OF OWNERSHIP RESULTS……………………..109
BIBLIOGRAPHY……………………………………………………………….112
VITA……….……………………………………………………………………...113

LIST OF ILLUSTRATIONS

Page

PAPER II

Figure 1. Lithium Global End-Use Markets (2010) 43

Figure 2. Evolution of Lithium Price: 1980-2010 53

Figure 3. Lithium/EV Supply Chain Showing Risks Factors and Constraints 62

PAPER III

Figure 1. Annual Publication Output 79

Figure 2. Distribution of Research by Country 81

Figure 3. Top 5 Countries Publishing EV Research 82

LIST OF TABLES

Page

PAPER I

Table 1. Description of Electric Vehicle Types 10

Table 2. Characteristics of the Sample Population..17

Table 3. Experience with AFVs 18

Table 4. Ranking of Electric Vehicle Attributes 21

Table 5. Summary of Chi Square Results..21

Table 6. Concerns about EVs..22

Table 7. Comparison of Vehicle 10-Year Cost of Ownership 25

Table 8. Actual Daily Driving Distance vs. Preferred BEV Range 28

Table 9. Ranking of Electric Vehicles Based on Environmental Sustainability..............30

Table 10. Perceptions of Sustainability of EVs Relative to other Vehicles 31

PAPER II

Table 1. Summary of Articles by Topical Area 49

Table 2. Focus of Reviewed Articles..51

Table 3. 2009/2010 World Lithium Mine Production and Reserves 52

Table 4. Recent Lithium Reserve and Resource Estimates 53

PAPER III

Table 1. Distribution of Research by Institution..82

Table 2. Distribution by Source Title 83

Table 3. Classification by Subject Area (2000-2011) 85

Table 4. Author Generated Keywords. 85

Table 5. Top Cited Papers in EV Research..86

1. INTRODUCTION

1.1. BACKGROUND

The transportation sector accounts for about 27% of global energy consumption (IEA, 2010). This sector obtains most of its energy from the combustion of petroleum-based fuels and is currently responsible for over half of global oil demand (IEA, 2012). Furthermore, this energy use is projected to increase with the growth of vehicles in both developed and developing countries. As a result, greenhouse gas emissions from transportation, mostly in the form of CO_2, will likely increase. This implies that the current transportation system is unsustainable.

Three major factors have led to the advancement of alternative fuel vehicles (AFVs) worldwide. First, there are increasing concerns over greenhouse gas emissions from transportation and the associated climate change. Secondly, the volatility of oil prices is causing nations to focus on alternative sources of energy. Finally, concerns about energy independence have resulted in policies targeting AFV development to reduce dependence on petroleum from foreign sources, some of which are unstable.

Electric vehicles (EVs) including hybrid electric vehicles, battery electric vehicles, and plug-in hybrid electric vehicles are a viable near-term AFV technology capable of addressing some of the problems facing the transportation sector. Policy-makers seeking to increase energy security, reduce air pollution and mitigate climate change increasingly favor EVs. This support is reflected in the increase in policies and funding to support the growth of the technology. In addition, almost all major car manufacturers are demonstrating interests in EVs and developing new passenger and commercial cars (Lieven et al., 2011).

Despite potential advantages of EVs, significant barriers remain to widespread adoption of the technology and currently, they represent a small market share of vehicles in service. Previous research suggests that battery technology limitations and high battery cost are the major obstacles to widespread adoption of EVs (Axsen et al., 2010). However, we argue that this view does not reveal other key areas that may likely affect the advancement of the technology. Transportation systems are forms of socio-technical systems whose success and sustainability are dependent on both social and technical factors. It is important to view EVs as part of a socio-technical system in order to break the divide between the technical and the social. The term “social-technical” encompasses technological, cultural, social, political and economic barriers (Sovacool and Hirsh, 2009). This research focuses on two socio-technical issues that affect widespread adoption and sustainability of EVs, barriers to consumer acceptance of the technology, and supply chain risks of raw materials for EV battery technology.

A major barrier is that consumers tend to resist new technologies that are considered alien or unproved; thus, engineering and policy decisions that consider their critical concerns will have a higher level of success. This study identifies potential socio-technical barriers to consumer adoption of EVs and determines if sustainability issues influence consumer decision to purchase an EV. In addition, this research employs statistical analysis to provide valuable insights into preferences and perceptions of technologically minded consumers.

The second part of this research focuses on the supply chain analysis of lithium, which is a major raw material for lithium-ion batteries used in EVs. State-of-the-Art Matrix Analysis (SAM) is used to assess the global EV battery raw material supply chain, and identify potential issues with the security and supply of lithium for production of lithium-ion batteries. Furthermore, this study develops a supply chain model with which to investigate the technical, geopolitical, and economic factors that affect the supply of lithium through different life cycle stages.

Finally, this research uses a bibliometric methodology to identify trends in EV research and proposes policy directions that will advance EVs along the innovation curve. The methodological approach used in this analysis shows a clear indication of general trends in EV research and technology and provides a quantitative analysis of the state of art of EVs.

1.2. RESEARCH OBJECTIVES

As concerns over the environment, energy security and escalating oil prices grow, there is a strong need to transform the transportations system and make it more sustainable. Thus, sustainability has become a major issue in the transportation sector. EVs could provide an intermediate solution to these problems facing the transport sector. Despite the many benefits of EVs, they are several issues that need to be considered as they may affect the long-term sustainability of this transportation technology.

The objective of this study is multifold. The overall objective of this research is to study EVs from a socio-technical perspective or a systems view to bridge the gap between social and technical aspects of the system. This approach is intended to capture important dynamics and interactions involved in EV adoption The first objective is to determine the factors that influence technology enthusiasts to have favorable (or unfavorable) perceptions about EVs. In addition, this research determines if sustainability influences these individuals' perceptions of EVs. The second objective is to determine the risk factors associated with lithium supply for EV batteries. This study aims to develop a framework to assess various risk factors that influence the supply of lithium throughout its life cycle. The third objective of this research is to use a bibliometric methodology to determine the status of EV research and the role of policy in advancing this technology.

1.3. RESEARCH CONTRIBUTION

This research has significant implications for both engineers and policy makers. This research has shed light on the socio-technical issues facing EVs from three main perspectives including 1) a consumer perspective 2) a supply chain or critical material supply perspective and finally 3) from a research and policy perspective. This study has provided insight into the attitudes of technological minded people towards EVs. These individuals are critical to the success of any new technology. Technology enthusiasts, though they represent a small percentage of the general population, are usually trendsetters for technology and therefore their early adoption makes this technology more visible to the rest of the market. Their endorsement of the EV technology may convince other consumers to adopt the technology. Second, this research clearly defines risk factors in the lithium supply chain and develops a supply chain model that can be used to study risks that affect lithium supply for EV batteries. This research is particularly important because it is expected that lithium-ion batteries will be used increasingly in EVs. As a result, it is critical to understand, manage, and mitigate uncertainties and risks in the supply chain in a smarter, more informed way. Finally, this study evaluates the current state of the EV technology and proposes recommendations directed at both the academic and policy community to advance the technology.

1.4. DISSERTATION OUTLINE

The dissertation is presented as a publication option, which consists of three journal articles. These journal articles are presented in the next section. The first paper is titled “Barriers to Widespread Adoption of Electric Vehicles: An Analysis of Consumer Attitudes and Perceptions.” This article determines the sociotechnical barriers to EV adoption and provided insight into the attitudes of technology enthusiasts. This is followed by second and third papers titled “Critical Issues in Supply Chain of Lithium for Electric Vehicle Batteries” and “A Bibliometric Analysis of Electric Vehicle Research: Evaluating the Technology and the Role of Policy, respectively. Finally, Section 2 summarizes the findings and implications of the dissertation.

PAPER

I. BARRIERS TO WIDESPREAD ADOPTION OF ELECTRIC VEHICLES: AN ANALYSIS OF CONSUMER ATTITUDES AND PERCEPTIONS

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Abstract

Electric Vehicles (EVs) are promoted as a viable near-term vehicle technology to reduce dependence on fossil fuels and resulting greenhouse gas (GHG) emissions associated with conventional vehicles (CVs). In spite of the benefits of EVs, several obstacles need to be overcome before EVs will be widely adopted. A major barrier is that consumers tend to resist new technologies that are considered alien or unproved, thus, policy decisions that consider their critical concerns will have a higher level of success. This research identifies potential socio-technical barriers to consumer adoption of EVs and determines if sustainability issues influence consumer decision to purchase an EV. This study provides valuable insights into preferences and perceptions of technology enthusiasts; individuals highly connected to technology development and better equipped to sort out the many differences between EVs and CVs. This group of individuals will likely be early adopters of EVs only if they perceive them to be superior in performance

compared to CVs. These results can guide policymakers in crafting energy and transportation policy. It can also provide guidance to EV engineers' decision in incorporating consumer preference into EV engineering design.

Key Words

Electric Vehicles, Consumer Attitudes, Socio-Technical Barriers

1. Introduction

The transportation sector is responsible for approximately 14% of global greenhouse gas emissions and this is projected to increase to 50% by 2030 (IEA, 2007). This projection implies that the current transportation system is unsustainable. A transformation of the global transportation sector is necessary to reduce greenhouse gas emissions, air pollution and dependence on fossil fuels. Electric Vehicles (EVs) are a viable near-term transportation technology capable of providing sustainable mobility. In the U.S., large deployment of EVs can play a significant role in addressing some of these problems (Natural Resources Defense Council, 2007). Recently, the U.S. government allocated considerable stimulus funding to promote the use of alternative fuels (Skerlos and Winebrake, 2010). The American Recovery and Reinvestment Act (ARRA) of 2009 provides over $2 billion for electric vehicle and battery technologies, geared toward achieving a goal of one million electric vehicles on U.S. roads by 2015 (Canis, 2011). These investments and targets imply that U.S. policymakers accept that large scale adoption of electric drive vehicles may be a sustainable solution to growing environmental, economic and energy concerns in transportation. In addition, almost all major car manufacturers are demonstrating interests in EVs and developing new passenger and commercial cars (Lieven et al., 2011).

Despite these potential advantages, significant barriers remain to widespread adoption of EV technology and currently, they represent a small market share of vehicles in service. Previous research suggests that battery technology limitations and high battery cost are the major obstacles to widespread adoption of EVs (Axsen et al., 2010). As a result, much research is aimed towards addressing the limitations placed on performance by the weight, bulk and storage capacity of batteries (Payton, 1988; Sovacool and Hirsh, 2009). However, we argue that this view does not reveal key areas of consumer resistance to EVs. It is important to view EVs as part of a socio-technical system in order to break the divide between the technical and the social. The term "social-technical" encompasses technological, cultural, social, political and economic barriers (Sovacool and Hirsh, 2009). According to Sovacool (2009), technologists and policymakers usually separate technical concerns from social concerns while describing technological development. However, the "social" barriers may pose as much of a problem as the "technical" in the development of EVs for the mainstream consumer market. In this study, we analyze socio-technical barriers particularly relating to consumers.

In this research, we investigate how differences in consumer populations change opinions and perceptions about EVs and can be used to determine potential socio-technical obstacles to EV adoption. We address two questions regarding EVs: 1) what are the socio-technical barriers to consumer adoption of EVs? And 2) how much influence does sustainability have on EV purchase decision? Using a survey administered to technology enthusiasts and potential EV owners, we categorize perceptions and preferences in order to identify the barriers to widespread acceptance of electric vehicles. The task of comparing the attitudes and perceptions of our sample with the general population is left to future research. This research considers functional attributes of EVs such as driving range, battery life and EV costs. Furthermore, we examine symbolic attributes which have been determined to influence consumer decisions in general vehicle use (Steg, 2005; Steg et al., 2001; Verhoef and Wee, 2000) as well as in the use of Hybrid Electric Vehicles (HEVs) (Heffner et al., 2007; Kahn, 2007; Turrentine and Kurani, 2007) and Battery Electric Vehicles (BEVs) Skippon and Garwood, 2011).

Insights gained from the results of this research will shed more light on public attitudes and preferences related to EVs. This information will guide policymakers in crafting energy and transportation policy based on the entire EV sociotechnical system. This research will also provide guidance to EV engineers' decision in incorporating consumer preference into EV engineering design.

2. Background

2.1. Electric Vehicle Technology

Conventional vehicles (CVs) have internal combustion engines (ICEs) that burn petroleum, operate inefficiently and emit a significant amount of greenhouse gasses. Alternative Fuel Vehicles (AFVs) are vehicles designed to operate on at least one alternative to petroleum and diesel and include EVs, bio-fuel vehicles, fuel cell vehicles, compressed natural gas vehicles etc. EVs or electric drive vehicles are vehicles in which partial or entire propulsion power is provided from electricity. EVs come in several varieties. The HEV combines the ICE along with an electric motor to achieve a higher fuel economy than similar-sized vehicles. Some commercially available HEVs include the Toyota Prius, Ford Escape Hybrid and Honda Civic Hybrid. The Plug-in Hybrid Electric Vehicle (PHEV) has a smaller internal combustion engine than the HEV and has a larger battery capable of powering the vehicle for distances between 20-60 miles (Sovacool and Hirsh, 2009). In addition, the PHEV battery is rechargeable and can be restored to full charge by connecting a plug to an external electric source. PHEVs offer the higher fuel efficiency of EVs within the all-electric range, but also the flexibility of conventional fuels for extended trips. Some examples of the PHEV currently in the market are the Chevrolet Volt and Toyota Prius Plug-in Hybrid. The BEV is powered solely by a rechargeable electric battery and has batteries that are usually larger than the PHEV and can travel for up to 100 miles on one full charge. BEVs represent a 'carbon free' mode of transportation if electricity for charging is generated from renewable include the Nissan leaf, Mitsubishi i-MiEV and Tesla Roadster. For the three categories of EVs shown in Table 1, there exist different variants each with a distinct range of electric driving depending on the battery capacity of the vehicle.

Table 1. Description of Electric Vehicle Types.

Vehicle Type	**Description**	**Benefits**
HEV	Electric vehicles that use an internal combustion engine in addition to an electric motor.	Better fuel economy, less expensive to run and lower emissions than similar conventional vehicles
PHEV	Electric vehicles with smaller internal combustion engine and more powerful electric batteries that can be recharged.	Better fuel economy, less expensive to run and lower emissions than similar HEVs and conventional vehicles. Offers flexibility of fuel source
BEV	Electric vehicles that derive motive power exclusively from onboard electrical battery packs that can be charged with a plug through an electric outlet.	No liquid fuels and zero emissions at tailpipe. Less expensive to run than similar HEVs and conventional vehicles.

The fundamental technological constraint to the commercialization of EVs is energy storage (Anderman, 2007; Mandel, 2007). According to Axsen et al. (2010), battery technology is limited by tradeoff between five major attributes including power, energy, longevity, cost and safety. Energy storage and energy density determine the range and mass of the battery system respectively. The battery range limits the distance an EV can travel on an all-electric range and on a single charge. The range issue has the greatest impact on BEVs, which do not have the flexibility of fuel source like HEVs and PHEVs and therefore may require charging en route during long trips that exceed the range of the batteries. Consequently, there is also a need for EV charging infrastructure to charge EVs during trips. In addition, high power is important because they translate into motive force for vehicle acceleration.

Battery cost is a key determinant in the economic viability of EVs especially PHEVs and BEVs. Pesaran et al. (2007) estimate that advanced batteries cost between $800 to $1000/kWh. One of the key goals of the U.S. Department of Energy (DOE) Vehicle Technology Program (2010) is to reduce cost of high-energy, high-power batteries from $1,200/kWh in 2008 to $300/kWh by 2014 to enable cost-competitiveness of PHEVs.

2.2. Consumer Attitudes and Motivation

Public attitudes and preferences for EVs must be considered in developing market share in this area. EVs must not only overcome the technological problems facing the battery technology but also social issues related to consumers in order to achieve commercial success. Consumer acceptance is crucial to the continuing success of a sustainable transportation sector (Ozaki and Sevastyanova, 2011). However, consumers tend to be resistant to new technology that is considered unfamiliar or unproven. Therefore, failure by EV manufacturers and policy makers to identify and overcome consumer issues may result in continued low acceptance of EVs long after the technical problems are resolved.

The theory of planned behavior (TPB) by Ajzen (1991) explains the factors influencing consumer behavior. According to TPB, the main determining factors of behavioral intention are attitudes, which are influenced by knowledge, and experience, subjective norms that the consumer believes is acceptable by society, and the perceived impact of the behavior. In this context, consumer acceptance of technology is considered an intention to adopt, use, or support its development (Ajzen, 1991). The main reasoning of the TPB is that actions are chosen based on an analysis of the alternatives through which the optimum outcome is achieved (Lane and Potter, 2007).

Research shows that some common barriers to the adoption of any new technology include lack of knowledge by potential adopters, high initial costs and low risk tolerance (Diamond, 2009). A study by Oliver and Rosen (2010) indicates that consumer acceptance of HEVs is limited partly due to perceived risks with new products and tradeoffs between vehicle fuel efficiency, size and price. The general public's perception of risk is based on experience, emotions, the media and other non-technical sources (Sjoberg, 1998). In general, media and social networks often influence values that affect consumer choices (Rogers, 2003; Lane and Potter 2007).

In terms of financial benefits, individuals are more likely to choose options that maximize utility based on their preferences, knowledge of alternatives and budget (Roche et al., 2010). The initial cost of an EV is significantly higher when compared to a gasoline powered ICE vehicle and this cost increases linearly with battery size or the range of the car. Duvall (2002) estimates that the extra cost of owning a HEV ranges between $2,500 and $14,000 compared to ICE vehicles. In Duvall's estimation, he used the average national gasoline price at the time, which was $1.65 per gallon. Due primarily to battery cost, EVs particularly PHEVs and BEVs are significantly more expensive than CVs. Another cost consideration is the price of gasoline. Van Bree et al. (2010) found that increase in gas prices influences consumer behavior. In a study on consumer adoption of HEVs, Gallagher and Muehlegger (2011) found that consumers usually make the decision to buy HEVs in response to increase in gas prices and government incentives.

Non-financial reasons, especially those associated with environment and energy can influence consumers' decisions to purchase an EV (Zpryme Research and Consulting, 2010). Hence, the potential for EVs to create social benefits by reducing petroleum consumption and GHG emissions can appeal to certain consumers. Environmental values are powerful predictors of certain consumer actions and positively influence willingness to engage in actions that protect the environment (Oliver and Rosen, 2010). Heffner et al. (2007) found that, to this group of consumers, who show high levels of environmental awareness, choosing a HEV symbolizes ideas related to one's individuality and is used to communicate interests and values. Studying HEV purchases in Los Angeles County, Khan (2007) found that environmentalists are more likely to purchase HEVs compared to non-environmentalists. Similarly, Gallagher and Muehlegger (2011) found that social preferences for environmental quality and energy security were a major determinant for consumer adoption of HEVs. Gallagher and Muehlegger concluded that social preferences increased HEV sales more than rising gas prices or tax incentives.

Furthermore, historical trends in technology adoption suggest that while new technology is intrinsically attractive to a few early adopters, including visionaries and technology enthusiasts, the majority of consumers will remain close-minded about the new technology (Moore, 2002). This small group of early adopters has positive attitudes to novelty and is likely to adopt new technologies (Heffner et al., 2007). On the other hand, some individuals are uncomfortable with technological change and uncertainty, and therefore are hesitant to accept innovations (Edison and Geissler, 2003). According to Modal (1999), 50% of Americans are technology pessimists; are averse to technology. The majority of consumers, while making choices, stick to “notions of tradition and familiarity…’ rather than embracing a new technology (Sovacool and Hirsh, 2009).

In recent times, however, there are increasing reasons to adopt EVs including rising and volatile gasoline prices, greenhouse gas emissions, increased dependence on imported petroleum, and the very high fuel economy of EV.

3. Methodology

3.1. Survey

An internet-based survey (see appendix A) was developed and used in this research to collect data from a sample population. The target population comprised mainly of current owners of CVs with the intention of capturing opinions, perceptions and attitudes of individuals who are prospective owners of EVs. Data was collected from students, faculty and staff at a technological university that specializes mainly in science, technology and engineering undergraduate and graduate programs. In terms of knowledge considerations, we consider the vast majority of the sample population as technology enthusiasts. Technology enthusiasts are individuals that are better connected with global technology development, have high level of quantitative skills and are more equipped to sort out the many technological, financial and environmental differences between EVs and conventional gasoline powered vehicles. For this study, we consider these individuals to be likely early adopters only if they perceive EVs to be superior in performance compared to ICE vehicles.

Over 500 responses were received but some were rejected due to incompleteness. As a result, 481 responses were used for further analysis. The main objective of the survey was to characterize potential EV owners in order to elucidate knowledge, interests, perceptions, attitudes, and barriers pertaining to EVs as well as views on sustainability. A secondary purpose of the survey is to relate certain socio-economic characteristics including age, education, gender, experience and income to the individual perceptions and attitudes towards EVs. We hypothesize that these factors would influence individual attitudes and perceptions. Furthermore, we test to see if there are any statistical differences between students and non-students.

The survey included four sections. The first section of the survey asked for respondent's gender, age, and other socio-economic details. Respondent's perceptions and attitudes towards EV attributes were examined in the second section. In the third section, respondents were questioned about environmental and sustainability issues.

Finally, in the fourth section, respondents were asked changes desired in the EV technology and pressing questions.

3.2. Statistical Data Analysis

The chi-square test was employed to investigate the differences in perceptions and attitudes among the sample population (Greenwood and Nikulin, 1996; Janes, 2001). The chi-square test for two-way tables is in the form of

$$Q_p = \sum_{i=1}^{s}\sum_{j=1}^{r}\frac{(n_{ij}-m_{ij})^2}{m_{ij}}$$

And

$$m_{ij} = \frac{n_i n_{ij}}{n}$$

Where m_{ij} is the expected value of the frequencies in the i^th row and j^th column and n_{ij} are marginal totals. Q_p is the Pearson chi-square statistic and has an asymptotic chi-square distribution with (s – 1) (r – 1) degrees of freedom when the row and column variables are independent.

The chi-square test is used to investigate statistical association between variables. This is done primarily by testing the null hypothesis of no association between a set of groups and outcomes for a response. For large values of Q_p, this test rejects the null hypothesis in favor of the alternative hypothesis of general association. We use the standard 5 percent or 0.05 cut-off for defining what is a statistically significant difference. Therefore an associated *p*-value < 0.05, means that there is significant evidence of an association between variables.

In the following sections, we summarize the results from the surveys and then relate the responses based on different categories.

4. Results and Discussion

4.1. Sample Description

The sample has a significantly higher representation of males (71%) compared to females (29%). The overall sample is relatively young with majority of respondents (88%) between the ages of 18 and 44. The age of respondents can be attributed to the fact the majority of the population are undergraduate and graduate students. From an education standpoint, the majority (84%) of the sample is working towards or has completed an undergraduate degree or graduate degree. One should note that the sample collected may not necessarily be representative of the general population; however, it provides helpful information about technology enthusiasts. Detailed demographic attributes of the sample are presented in Table 2.

Table 2. Characteristics of the Sample Population.

Sample Attributes		%
Sample Size		481
Gender	Male	71%
	Female	29%
Ethnicity	White	85%
	Asian	7%
	African American	2%
	Hispanic Latino	1%
Age	18-24	62%
	25-44	26%
	45 and over	12%
Occupation	Students	80%
	Faculty	11%

Table 2. Characteristics of the sample population (Cont.)

Education	Some College/Associates	14%
	Undergraduate (Complete/in progress)	51%
	Graduate (Complete/in progress)	32%
Household Income	Under $25,000	22%
	$25,000-$49,999	15%
	$50,000-$74,999	16%
	$75,000-$99,999	12%
	$100,000 and above	20%

4.2. EV Knowledge, Experience and Interest

Fifty-three percent of the sample had some experience with AFVs and 47% (n=225) reported having no experience. Further breakdown of survey results shown in Table 3 illustrates that 38% had experience with HEVs, 17% with BEVs and 7% with PHEVs.

Table 3. Experience with AFVs.

Experience with Electric Vehicles and Other Alternative Fueled Vehicles		
	Number of responses	%
None	225	47%
Hybrid Electric	184	38%
Battery Electric	80	17%
Biofuel	67	14%
Plug-in Hybrid Electric	36	7%
Other	20	4%

Chi-square analysis showed that there were significant differences in prior experiences with AFVs based on gender (Q_p=17.442; df =1, p = <0.0001). The results suggest that males were more likely than females to indicate some experience with EVs. Moreover, no significant differences based on age (Q_p=3.801, df=2, p=0.1495), level of education (Q_p=2.0976, df=1, p=0.1475), and income (Q_p=7.7106, df=3, p= 0.0524) were observed. Differences between students and non-students was also not statistically significant (Q_p=0.0005, df=1, p= 0.9829). In gauging awareness of particular EV types, respondents identified that they were most aware of HEV (95%) followed by PHEV (81%) and lastly BEV (76%). It is interesting to see that the level of awareness reflects the technology curve and the market; HEVs are most prevalent in the market, PHEVs, which are not as widespread as HEVs, are more popular than BEVs are.

Respondents were also asked to rate their interest in AFVs on a 4 point likert scale from 1 (no interest) to 4 (high interest). Considering that the majority of the sample consists of engineers or engineers in the making our initial hypothesis was that a strong interest towards AFVs would be evident. The majority of the population indicated moderate (43%) or high interest (38%) in AFVs. The overall average rating of self-reported interest in AFVs was a composite score of 3.14 out of 4. Chi-square tests showed statistically significant association between interest in AFV, gender (Q_p=15.6035, df=3, p= 0.0014) and education (Q_p=12.4608, df=3, p= 0.006). Again, males were more likely than females to indicate some interest in AFVs. In addition, individuals with graduate degrees expressed more interest in AFV than those individuals with undergraduate or lower degrees. When asked specifically about interests in EVs, respondents showed less interest. There were significant differences in interests in EVs based on gender, education and age. There were no statistically significant differences in interest based on income. Furthermore, there were no statistical differences between the student population and the non-student population. As was the case with interests in AFVs, males and individuals working towards or had completed a graduate degree expressed more interest in EVs. The level of appeal of different types of EVs to respondents followed the same trend as respondents' level of awareness of EV types, with HEVs being ranked as the most appealing type of EV followed by PHEVs and then BEVs.

Most associations with EVs were with regard to environment, battery performance and charging, efficiency, high purchase cost, fossil fuels, alternative energy and the future in that order. Respondents who generally had a very positive view of EVs cited the efficiency of EVs in terms of fuel saving; "higher MPG" and "non-gas-guzzler". Furthermore respondents referred to EVs as the future of transportation; "the way of the future" and "future of travel. Environmental benefits were also associated with EVs; "green", "zero emissions" and "environmental friendly". Negative associations with EVs included high purchase cost, limited battery longevity, battery range, long recharging time, and environmental impacts from increased fossil fuels use at power plants to generate electricity for charging EVs.

Results showed an average likelihood to purchase an AFV with an overall interest composite score of 2.59 out of 4; 49% of respondents indicated that they were either likely or very likely to purchase an AFV. Thirty seven percent and 15% chose 'somewhat likely' and 'not at all likely' respectively. Chi Square test showed no statistical significant differences in likelihood to purchase an AFV based on gender (Q_p=2.6291, df=3, p= 0.4524), age (Q_p=6.8569, df=6, p= 0.3343), income (Q_p=0.4589, df=3, p= 0.2668), and level of education (Q_p=2.5921, df=3, p= 0.4589). There were also no significant differences between students and non-students (Q_p=2.6318, df=3, p= 0.4519).

Furthermore, respondents identified decrease or elimination of the use of petroleum as the most appealing attribute of an EV followed by lower maintenance costs and then greenhouse gas reduction (See Table 4). Comfort and style received the lowest ratings. A summary table showing chi-square results is shown in Table 5.

Table 4. Ranking of Electric Vehicle Attributes.

Ranking of EV Attributes							
Attribute	**5 (most appealing)**	**4**	**3**	**2**	**1 (least appealing)**	**Mean (N=438)**	**Std. Dev. (N=438)**
Decrease/eliminate the use of petroleum	176 40%	91 21%	48 11%	59 13%	64 15%	3.5845	1.4808
Less maintenance	88 20%	100 23%	146 33%	57 13%	47 11%	3.2853	1.2287
Reduced greenhouse gas emissions	70 16%	100 23%	93 21%	74 17%	101 23%	2.9178	1.3972
Looks/style	48 11%	64 15%	65 15%	100 23%	161 37%	2.4018	1.3875
Comfort	56 13%	86 20%	83 19%	148 34%	65 15%	2.8174	1.2672

Table 5. Summary of Chi Square Results.

Variables	**Demographics**											
	Gender			**Age**			**Education**			**Income**		
	Q_p	df	p-value	Q_p	df	p-value	Q_p	df	p-value	Q_p	df	p-value
Concerns	14.2165	5	0.0143	12.2402	10	0.2692	8.689	5	0.1221	17.0461	15	0.316
Safety	30.5974	5	<.0001	17.2026	10	0.0700	10.0075	5	0.075	24.0643	15	0.064
Experience with AFVs	17.4419	1	<.0001	3.801	2	0.1495	2.0976	1	0.1475	7.7106	3	0.0524
Familiarity with 'Sustainability'	0.4398	1	0.5072	7.3624	2	0.0252	6.0624	1	0.0138	5.857	3	0.1188
Interest in AFV	15.6035	3	0.0014	8.385	6	0.2112	12.4608	3	0.006	6.4584	9	0.6933
Interest in EV	23.3997	3	<.0001	15.2957	6	0.0181	15.363	3	0.0015	5.6689	9	0.7725
Likelihood to Purchase AFV	2.6291	3	0.4524	6.8569	6	0.3343	2.5921	3	0.4589	11.1313	9	0.2668
EV Sustainability	23.492	4	0.0001	7.0611	8	0.5301	9.276	4	0.0546	5.3243	12	0.9463

4.3. Concerns about EVs

Overall, EV battery range limitation was cited as the biggest concern (33%, n=141) followed by high cost (27%, n=117) and charging infrastructure (17%, n=58). These concerns reaffirm some of the issues identified initially by respondents when asked about associations with EVs. Chi-square analysis showed significant evidence of an association (Q_p=14.2165, df=5, p= 0.0143) between concerns and gender with the largest number of males expressing concern about battery range while the largest number of females were most concerned about cost. There were no statistically significant differences in concerns based on age, education, income or between students and non-students. A full breakdown of concerns is presented in Table 6.

Table 6. Concerns about EVs.

Biggest concern about EVs		
	Number of responses	%
Battery range	158	33%
Cost	129	27%
Charging infrastructure	83	17%
Other	58	12%
Reliability	47	10%
Safety	6	1%

Despite the fact that less than 1% of respondents identified safety as the most important concern, only 57% of the respondents agreed or strongly agreed that EVs are a safe mode of transportation while 26% indicated they were unsure. The large number of ‘unsure’ responses suggests that there is limited understanding of EV safety even among technology enthusiasts. Differences in responses regarding EV safety were statistically significant based on gender (Q_p=30.5974, df=5, p= <.0001) with males (27%) more likely to strongly agree that EVs were safe compared to females (10%). Also, females were more unsure and neutral about the safety of EVs compared to males. Furthermore, individuals that indicated some experience with AFVs were more likely to strongly agree that EVs were safe compared to individuals lacking experience. Individuals that had no prior experience with EVs were more uncertain about EV safety at 16% compared to only 4% of individuals who indicated having some experience with EVs. These findings indicate a relationship between prior experience and perceptions of EV safety. Exposing individuals to EVs will likely reduce perceptions of EVs as being unsafe.

The average cost of gasoline ($/gallon) at which respondents (n=395) will be persuaded to purchase an EV was calculated to be $5.42/gallon with confidence interval of $1.75 and using α =0.05. The mode and median were $5.00 and $5.00 respectively. There was a wide range of gas prices given and several individuals indicated that price is conditional on factors such as initial cost of the EV, electricity cost, performance and range. A considerable number of respondents showed unconditional willingness to purchase EVs by indicating that they needed no persuasion to purchase an EV whereas a few respondents expressed strong resistance and indicated they will 'walk first' implying that drastic increase in gas prices alone was not enough incentive to purchase an EV. Mainly individuals with this position indicated prices ranging from $50 to an infinite amount of dollars. There was considerable skepticism among respondents and the word 'depends' featured considerably in responses. In general, the results are consistent with findings of Diamond (2009) that as long as PHEV purchase price is high, market penetration will not increase significantly unless gasoline prices rise. The same reasoning can also be applied to the adoption of HEVs and BEVs as our results indicate a relationship between general EV adoption and gasoline price. This finding suggests that higher gasoline prices together with lower EV purchase price will positively impact market penetration of EVs. As gas prices rise, more people consider EVs to be worthwhile investments. Consequently, a significant number of the sample population believe that prices will rise in the future and that purchase of an EV represent an intelligent response to the higher prices.

Our results are contrary to a previous study on EVs that show that cost is the main attribute governing vehicle purchase decision (Zpryme Research and Consulting, 2010). The expectation in this study was that cost would be the greatest concern considering that the majority of our sample population consists of college students earning limited income. However, the fact that cost was ranked lower than battery range may be ascribed to that fact that the technologically minded target group is more likely to rank technical problems higher than financial problems.

A comparison of the 10-year cost of ownership for a CV (Chevy Cruze), a HEV (Toyota Prius), a PHEV (Chevy Volt) and a BEV (Nissan LEAF) is presented in Table 7. The CV, HEV and PHEV in this study have a combined fuel economy of 30 miles per gallon (mpg), 50 mpg, and 37 mpg respectively. In addition, the PHEV and BEV use lithium-ion batteries that are capable of an all-electric range of 35 miles and 100 miles respectively. It is assumed that the vehicles are driven for 15,000 miles per year over a period of 10 years. The cost is calculated for two different gasoline price scenarios. The cost of ownership at the average 2011 U.S regular gasoline price of $3.52/gallon is compared with $5.42/gallon which is the average gasoline price indicated by the study sample. The baseline manufacturer's suggested retail price (MSRP) for each vehicle was used. The cost of electricity for charging the PHEV and BEV is held constant at 11.9 cents/kWh based on the 2011 U.S. average residential electricity retail price. The maintenance and repair costs are obtained from Kelly Blue Book, which provides five-year ownership costs for vehicles.

Table 7. Comparison of Vehicle 10-Year Cost of Ownership.

10-Year Vehicle Ownership Cost								
	$3.52/Gallon Gasoline				$5.42/ Gallon Gasoline			
Item	**CV(Chevy Cruze)**	**HEV (Toyota Prius)**	**PHEV (Chevy Volt)**	**BEV (Nissan Leaf)**	**CV(Chevy Cruze)**	**HEV (Toyota Prius)**	**PHEV (Chevy Volt)**	**BEV (Nissan Leaf)**
Vehicle purchase price	$16,800	$24,000	$39,145	$35,200	$16,800	$24,000	$39,145	$35,200
EV Battery Replacement	-	$3,000	$5,300	$7,700	-	$3,000	$5,300	$7,700
240V Charger Installation	-	-	-	$2,200	-	-	-	$2,200
Repairs	$5,480	$4,624	$5,424	$4,480	$5,480	$4,624	$5,424	$4,480
Maintenance	$6,496	$5,331	$5,060	$4,846	$6,496	$5,331	$5,060	$4,846
Gasoline	$17,605	$10,563	$2,117	$0	$27,100	$16,260	$3,259	$0
Electricity	0	0	$5,603	$4,284	-	-	$5,603	$4,284
Total	**$46,381**	**$47,518**	**$62,649**	**$58,710**	**$55,876**	**$53,215**	**$63,791**	**$58,710**
Total with AARA 2009 Incentive			**$55,149**	**$51,210**			**$56,291**	**$51,210**

After the fifth year, we assume that repair and maintenance costs remain constant throughout the rest of the vehicle lifetime. Currently the EVs under consideration have warranties on batteries for 8 years/100,000 miles. We assume that the EV batteries will need replacing at the end of the warranty period. The U.S. DOE vehicle technologies program 2014 goal of $300/kWh is used to calculate battery cost for the 16 kWh and 24 kWh lithium-ion batteries of BEV and PHEV respectively. A local Toyota dealership provides an estimate of approximately $2,500 for a new Prius nickel-metal hydride battery with roughly $500 for installation. This installation estimate is also added to the PHEV and BEV battery replacement cost. Finally, we consider the impact of the 2009 ARRA $7,500 tax credit on the cost of ownership of the PHEV and BEV. This calculation does not consider other direct costs such as depreciation, insurance, registration and vehicle taxes.

At $3.5/gallon of gasoline, the additional cost of ownership compared to a CV is $1,137, $16,268 ($8,768 with tax credit) and $12,329 ($4,829 with tax credit) for the HEV, PHEV and BEV respectively. At $5.42/gallon of gasoline this cost is reduced to -$2,661, $7,915 ($415 with tax credit) and $2,834 (-$4,666 with tax credit) for the HEV, PHEV and BEV respectively. Our calculations indicate that at $5.42/gallon of gasoline the BEV and PHEV are economically competitive if AARA incentives are considered. The difference in cost of ownership between the EVs and CVs are significantly higher partly due to battery replacement costs. Therefore, if EV battery lifetime is improved and/or battery cost further reduces this cost difference will be less.

4.4. Battery: Driving Range and Battery Charging

In terms of fuel source and storage, EVs (particularly BEVs) have two disadvantages compared to ICE vehicles; EV batteries are more expensive and bulky, and refueling is typically slow; approximately 1-20 kW for electric versus 5000 kW for gasoline (Pearre et al., 2011). This means that initial BEVs, which rely solely on onboard batteries, will have less range than gasoline powered vehicles, and cannot be quickly refueled en route. These problems do not impact PHEVs as much because they can be refueled by either electricity or liquid fuels. With regard to our driving range analysis, this study focuses mainly on BEVs because they present the greatest range limitation.

The majority of respondents (71%) travel fewer than 20 miles per day, 79% travel fewer than 30 miles per day while 87% travel fewer than 40 miles per day. These results are consistent with the National Household Travel Survey (2011) which shows that on average a person travels about 36 miles. Our analysis shows that even with limited range, first-generation PHEVs and BEVs, which are generally between 40 and 100 miles could provide a large percentage of daily travel needs, assuming that batteries are charged daily. However, occasional long trips may not be possible on BEVs without recharging the battery during the trip.

In general, greater range is more desirable but as the range of the battery increases so does the cost. The question is: what is the minimum range that you require before considering to purchase a BEV? Only 32% of respondents were interested in BEVs with a battery range between 0-100 miles, 23% chose ranges between 100 and 200 miles, while 45% chose ranges greater than 200 miles. The average minimum range desired was 215 miles. Table 8 compares actual daily driving distance to desired BEV range. These results stand in stark contrast to self-reported average daily driving distances. There is clearly a large gap between individual expectations of the driving range of a BEV and actually daily driving distance. This disparity may be partly due to range anxiety, which is the fear being stranded in a BEV because it has insufficient range to reach its destination. Battery technology is advancing rapidly and range limitations will not be a lasting problem (Pearre et al., 2011). If battery performance continues to improve at a steady rate then a major issue to be addressed is attracting an adequate market for EVs to support limited range EVs in the period before battery technology improves.

Table 8. Actual Daily Driving Distance (in miles) vs. Preferred BEV Range (in miles).

Average miles driven per day vs. Desired BEV range		
Distance/Range (Miles)	Average miles driven per day	Desired BEV range
Less than 10	47%	0%
11-20.	24%	0%
21-30	8%	4%
31-40	8%	2%
41-50	5%	9%
Greater than 50	9%	86%

Many responses indicated that choice of battery range would depend on how long it took to recharge the battery. Many respondents also indicated that if EVs could quickly be recharged on the go that they would not expect the range to be as great. Only 32% of the sample thought charging an EV was convenient compared to refueling a gasoline vehicle. Thirty-six percent of respondents consider charging an EV inconvenient whereas 32% were unsure.

Another option for long distance travel with EVs is the idea of battery swapping. Battery swapping refers to quickly replacing a EVs depleted battery with a fully charged one at a battery swap station. In this case, the battery ownership would likely be separated from vehicle ownership, meaning that the initial price of EVs would decrease but consumers would then pay for a monthly subscription, similar to a cell phone plan to cover the cost of the battery ownership and the price of recharging and/or swapping the battery. Thirty one percent of respondents indicated willingness to purchase an EV if the ownership of the battery and vehicle were separated and such a battery swapping plan were available for a monthly subscription. Twenty-five percent of respondents were against the notion of battery swapping, while 43% were unsure. An advantage of the battery swapping idea is the separation of the battery ownership from the vehicle. Considering that EV battery constitutes a large portion of the cost of the vehicle, early failure of the battery was a concern for some respondents because of the high cost of replacement. Despite being informed that EVs coming to the market today have warranties on their batteries of around 8-10 years, 42% of respondents indicated that they would be "very worried" about the degradation or possible failure of their EV's battery and 48% were "somewhat worried".

4.5. Sustainability of EVs as a Transportation Option

Eighty-three percent (n=401) of respondents indicated some familiarity with the concept of sustainability. In addition, 79% (n=379) of the sample indicated that sustainability influenced their decision when purchasing a vehicle. Chi-square analysis showed significant evidence of differences in familiarity with sustainability based on age (Q_p=7.3624, df=2, p= 0.0252) and education (Q_p = 6.0624, df = 1, p = 0.0138). More individuals working towards or had completed a graduate degree were familiar with the idea of sustainability compared to those working towards or had completed an undergraduate degree. Also, respondents in the 18-24 age range were more likely to be unfamiliar with the term sustainability compare to those ages 25 and above. Those respondents that indicated they were knowledgeable about sustainability were asked to provide a definition in their own words. Although definitions varied, three different categories were evident. The vast majority of definitions were related to product/resource longevity (32%), resource conservation (26%), and protecting the environment (14%). In addition, a number of respondents also provided overall definitions of sustainability that addressed environmental, economic and social dimensions; "having a zero net impact on environment, economy, and social structure."

BEVs were ranked the most environmentally sustainable EV, followed by PHEVs and then HEVs (see Table 9). This shows an inverse of the responses for awareness and appeal of EVs. A significant percentage (43%, n=206) of respondents were neutral about EVs being more sustainable than traditional CVs and other AFVs. The results, shown in Table 10, suggest that while sustainability considerations influence respondents' vehicle purchase choice, majority remain uncertain about sustainability of EVs compared to CVs and other alternatives. This view of EVs can be attributed to some comments made by

Table 9. Ranking of Electric Vehicles Based on Environmental Sustainability.

	Ranking of EV Sustainability				
Attribute	**3 (Most Sustainable)**	**2**	**1 (least Sustainable)**	**Mean(N=481)**	**Std. Dev. (N=481)**
BEV	220	94	167	2.13	0.8904
	46%	20%	35%		
HEV	126	148	207	1.83	0.814
	26%	31%	43%		
PHEV	135	239	107	2.06	0.7069
	28%	50%	22%		

respondents such as; "no use of fossil fuels in the car but increase fossil fuels used at power plants to fuel the car.", "Vehicles that run on electricity generated from gas or coal power", "transferring greenhouse gasses from roads to power plants" and "…aren't even green considering most of our electricity comes from coal plants". This finding implies that some individuals with high environmental awareness may not consider purchasing EVs as beneficial to the environment. Such perceptions of EVs serve as a potential obstacle to EV adoption.

Table 10. Perceptions of Sustainability of EVs Relative to other Vehicles.

Electric vehicles are more sustainable compared to traditional gasoline-powered vehicles and other alternatives		
	Number of responses	%
Strongly agree	32	7%
Agree	119	25%
Neutral	206	43%
Disagree	88	18%
Strongly disagree	36	7%

Differences based on gender (Q_p=23.492, df=4, p= 0.0001) were statistically significant with 57% of females being more neutral on the sustainability of EVs compared to 37% of males. There was no significance in differences based on education level. Individuals that indicated they consider sustainability before purchasing a vehicle indicated an average gas price of $5.20 in order to be persuaded to buy an EV compared to $6.30 for individuals that do not consider sustainability when making vehicle purchase decisions. This suggests that individuals with high sustainability awareness are likely to adopt EV technology sooner that individuals with low sustainability awareness.

4.6. Unaddressed Concerns about Electric Vehicles

In concluding the survey respondents were asked, “What, if anything, could be done to make you want to purchase an EV?” Some representative responses include; “Show me they are truly sustainable”; “I want something cost-efficient that doesn't burn a hole through my energy bill”; “Reduce Cost, Increase Range, Decrease Recharge Time” ; “Give a bigger tax credit. ”; “Evidence of its reliability, safety and cost savings”. Other comments include “Cost not much more than a gasoline ICE vehicle” and “Cost of gasoline reaches insane levels”.

The majority of respondents had questions relating to the battery technology, raw material supply, environmental impacts, appearance, operation and performance of EVs, cost, and how electric cars compare to conventional vehicles and other AFVs. Respondents were interested in learning more about the mechanisms of charging, how the battery range limitation can be overcome and how to secure the mineral resources necessary for large-scale battery manufacturing. Concerns about cost were evident because cost was the subject of several questions (17%); this includes the initial cost, maintenance cost and payback period. In addition, questions were asked about how EVs could be made more economically competitive to conventional gasoline powered vehicles. Some respondents wondered when EVs will become widely available and questioned if there were some battery problem which manufacturers were not being open about.

In terms of environmental impacts, the sampled individuals were very critical about environmental impacts of EVs especially regarding fuel sources for generating electricity to charge EVs. They demanded answers that disproved the notion that adoption of EVs was just “trading one problem for another’; reducing gasoline but increasing fossil fuel generated electricity. These responses indicate that some of the sampled technologically minded individuals question environmental impacts of EV and calls for more communication and debate on the subject. Questions posed showed gaps in the understanding of the environmental impacts of EVs because studies (Duvall et al., 2007; Jaramillo et al., 2009) have shown that PHEVs have the potential to substantially reduce greenhouse gas emissions. In addition, lifecycle analyses by Jaramillo et al. (2009) show that PHEVs emit 50% less greenhouse gas compared to gasoline and diesel vehicle fuels, even when coal is the primary source of electricity.

From the open-ended questions posed in the survey, it is evident that there was a somewhat strong awareness and understanding of the benefits and constraints of EVs. Considerable understanding of the comprehensive technical details of EVs may have contributed to more reserved judgment. This argues for more communication; otherwise, there is a risk of negative perceptions being embedded in public opinion.

5. Conclusions and Implications for Transportation Policymakers

The sample used in this study may not be representative of the entire population due to differences in environmental awareness, education and income of majority of respondents; however, it provides helpful insights into preferences and attitudes of technologically minded individuals. Our results show that attitudes, knowledge and perceptions related to EVs differ across gender, age, and education groups. Furthermore, our findings suggest that although sustainability and environmental benefits of EVs have a major influence on EV adoption they are ranked behind cost and performance. Overall, we conclude that a moderate to high interest in EVs exists despite several reservations expressed towards EVs. In general, attitudes towards EVs were neither wholly positive nor wholly negative, however, completely negative attitudes to EV technology detected, though minimal, should not be ignored.

Evidence provided in this study emphasizes the need to address socio-technical barriers facing EVs. As previously mentioned, some major challenges faced by EVs include battery technology, battery costs and charging infrastructure. However, consumer acceptance is important as it is key to the commercial success (or failure) of EVs, even if the other criteria are met. A major potential barrier to widespread EV adoption detected among our technologically minded target group is the uncertainty associated with the EV battery technology and sustainability of fuel source. Some of this uncertainty may be attributed to unfamiliarity with the EV technology but may also be due to the fact that several individuals in this group are not convinced that EVs are a better option than some currently available CVs. The fact that some members of this group question the sustainability and environmental performance of EVs compared to ICE vehicles may mean that some individuals with high environmental awareness or values may not consider the purchase of an EV as beneficial to the environment.

Current incentives such as tax credits to subsidize the cost of EVs and fuel taxes may have little effect on EV market penetration if consumers have low confidence in EV technology. Therefore, certain measures need to be taken to increase the market share of EVs. These measures, some of which are already being explored, include education, increased investments in EV technology, infrastructure, battery swap programs, strong warranties on the EV batteries and perhaps increased tax credits to subsidize the cost of

EVs. Since public opinion can be influenced through media and social networks, policy makers can use this medium to influence the public appreciation for non-financial benefits of adopting EVs such as energy security and reduction of ecological footprint

6. Future Work

This study focused on the perceptions and attitudes of a technological minded group towards EVs. Future research will compare the attitudes and perceptions of this sample with those of the general public in other to provide insight on how different types of consumers perceive EVs as well as to highlight individual similarities and differences between the two different consumer groups.

The cost of vehicle ownership discussed in this paper also leads to opportunities for future work. In Europe, gas prices are typically much higher compared to the United States. Therefore, without other incentives, consumers will likely be more motivated to purchase EVs in Europe than in the United States. A follow-up research will apply the same methodology used in this study to European data.

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II. CRITICAL ISSUES IN SUPPLY CHAIN OF LITHIUM FOR ELECTRIC VEHICLE BATTERIES

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Abstract

A combination of high fuel costs, concerns about petroleum availability, and air quality issues related to fossil fuel-based vehicles are driving interests in electric vehicles (EVs). In this article, we conduct an integrative literature review to assess the global EV battery raw material supply chain, and identify potential issues with the security and supply of lithium for production of lithium ion batteries. State-of-the-Art Matrix Analysis (SAM) is used to characterize literature into major areas of concern including resources/reserves, supply and demand, geopolitical environment, and recycling. Furthermore, we develop a lithium supply chain model that provides a framework with which to investigate the technical, geopolitical, and economic factors that impact the supply of lithium through different life cycle stages. Results of this research will provide the engineering manager with a better understanding of issues surrounding the lithium supply chain for EVs, and will facilitate decision-making.

Key Words

Electric vehicle, Supply chain, Sustainability, Lithium, Lithium ion Battery

1. Introduction

Currently, the transportation sector accounts for about 29% of greenhouse gas (GHG) emissions in the U.S (EIA, 2009). Under a business as usual scenario, emissions from American drivers is projected to increase by 55% between 2000 and 2020 (Friedman, 2003). Furthermore, the present energy economy based on fossil fuels is at serious risk due to several factors including the rapid depletion of petroleum resources, volatile oil prices and the dependence on politically unstable oil producing countries (Scorsati and Garche, 2010). This implies that dependence of the transportation system on oil is unsustainable.

Due to the implications of global warming, governments worldwide are taking actions to reduce GHG emissions in the transport sector (Bonilla and Merino, 2010). Widespread use of EVs—including hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs)—could reform the transportation sector and drastically reduce oil consumption (Daniel et al., 2011; Zackrisson et al., 2010), and associated GHG emissions. Nonetheless, several crucial issues need to be addressed in order to make EV supply chain sustainable. Among them, an obvious issue is the security and supply of raw materials for battery production. Presently there are several unanswered questions related to sustainability of the supply of some crucial raw materials needed for battery manufacture.

Several battery types have great potential for use in EVs including lead-acid (LA) batteries, Nickel-metal hydride (NiMH) batteries, and Lithium-ion (Li-ion) batteries (Bleischwitz, 2010; Wang et al., 2010; Wadia et al., 2011). There are also various promising alternative battery technologies for electric vehicles including metal air and sodium batteries (Wanger, 2011; Wray, 2009), but these technologies are still being developed and not yet competitive. Currently, Li-ion and NiMH batteries are the two prevalent kinds of batteries used in EVs. NiMH batteries are the predominant source of electric power for hybrid electric vehicles (HEV) (Majeau-Bettez et al., 2011). However, a shift to Li-ion batteries, which currently possesses clear performance advantages over other battery technologies, has begun. It highly likely that Li-ion batteries will be used in the next generation EVs especially with the increasing popularity of PHEVs and BEVs (Gruber and Medina, 2011; Scrosati and Garche, 2010, USDOE, 2011). In addition, Li-ion batteries may also gain a considerable share of HEV market (USDOE, 2010).

Due to the potential for Li-ion batteries as power sources of choice for sustainable transport, this paper focuses on lithium, which is a key raw material utilized in the manufacture of Li-ion batteries. It is important, while designing a supply chain, to address demand uncertainty and changes in market conditions over time (Butler et al., 2006). Considering the importance of lithium to the future of EVs, instability and uncertainties in the present supply places the global energy and environmental sustainability goals at risk.

In this study, several critical issues in the lithium supply chain are explored to identify major risk areas. We use an integrative literature review to discuss the current state of knowledge related to lithium supply chain. By assessing the evidence in the literature, this analysis is intended to present a more comprehensive perspective of the topic, identify gaps in the current state of knowledge and determine directions for future research. This will be achieved by a SAM analysis of past literature related to lithium supply chains and implications for EVs. The three primary research questions in this study are (1) What are the lithium supply chain issues and risks related to EVs described in the literature? (2) What new knowledge related to Li supply chain has emerged in the literature between 2001 and 2012? (3) What are the gaps in the literature?

2. Overview of Lithium and Electric Vehicle Batteries

2.1. Lithium

Lithium, the lightest solid element, is an excellent conductor of electricity and heat. Given these properties, lithium is used in a variety of processes. Although, lithium will be used significantly in future automotive applications, the glass and ceramic industry is currently the major consumer of lithium. The United States Geological Survey (USGS) estimates of the major global end-use markets as Figure 1 shows include; ceramics and glass, 31%; batteries, 23%; lubricating greases, 9%; air treatment, 6%; primary aluminum production 6%. Another use that may have a considerable impact on future demand of lithium is in nuclear fusion (Fasel and Tran, 2005). However, it is unlikely that a major advance will be made in this application in the near term (Ebensperger et al., 2005).

High-performance lithium secondary or rechargeable batteries are used in several applications such as cameras, cell phones electric vehicles and laptop computers. Currently, batteries, particularly secondary batteries, are the fastest growing end use of lithium, increasing from 6% of lithium use in 2000 to over 20% in 2010 (Hensel, 2011). Therefore, it is expected that batteries will be main lithium consumer in the near future.

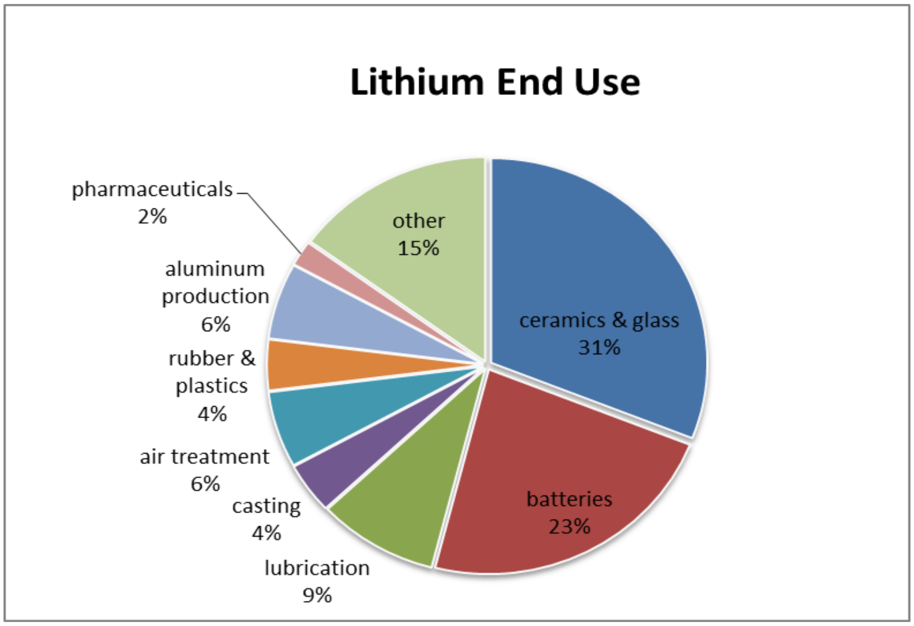

Figure 1. Lithium Global End-Use Markets (2010)

Source: USGS (2011)

The two main sources of lithium are lithium minerals and lithium containing brines and are used to produce lithium carbonate, lithium chloride, lithium hydroxide, lithium metal and other lithium based products. A resource as defined by the USGS is "…a naturally occurring solid, liquid, or gaseous material in or on the earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible" (USGS, 2011). Reserves are commodities that "… could be economically extracted or produced at the time of determination". This means that reserves are parts of resources that can be extracted using the existing technology at the current market price. According to estimates by Gruber et al. (2011), brines make up 66% of global lithium resource. Brines are mainly found naturally in areas where lake water has evaporated and are extracted and pumped into shallow evaporation ponds where they are evaporated under controlled conditions to extract the lithium. Brine salt flats contain the highest concentration of lithium. Current lithium production is mainly from high concentrations of lithium found in salt brines (Bradshaw et al., 2011), where lithium is produced as lithium carbonate (Fasel and Tran, 2005). This is due to lower production costs compared with the mining and processing costs for hard-rock ore (USGS, 2011). As a result, most lithium production through extraction from minerals is no longer economically feasible (Fasel and Tran, 2005). The most important brines are those located in the Andes and China. Salars or "salt flats" in the Spanish language, in Chile and Argentina, have high concentrations of lithium and are important sources of lithium carbonate used in EV batteries. In addition to having the highest concentration of lithium, the Salar de Atacama in Chile is the world's largest producing deposit of lithium (Gruber et al., 2011). Salar de Uyuni in Bolivia, which has a lower lithium concentration than Atacama, is estimated to contain the largest lithium resource in the world but currently does not produce lithium.

Lithium is highly concentrated in just a few regions. Five countries, Bolivia, Chile, China, United States and Argentina, represent roughly 90% of global resources. The majority (over 50%) of the world's lithium reserves and production exist in South American countries including Chile and Argentina. In addition, Australia, and China have considerable Li reserves. Bolivia's lithium deposit is currently not considered economic, but has potential to become economic in the future (USDOE, 2011). Currently, Bolivian mining operations are nearly nonexistent, and it is uncertain when a lithium project on the Salar de Uyuni will be fully developed.

2.2. EV Battery Application

Li-ion battery technology is the focus of future EVs because it is considered the best option that can effectively circulate HEVs, PHEVs, and BEVs at high levels (Scrosati and Garche, 2010). Therefore, its adoption continues to gather momentum. It is projected that future longer-range lithium use in EV batteries will be the major driver of demand for lithium for battery segment (Anderson, 2011). Consequently, supply of lithium as a raw material is also a potential catalyst that will determine the sustainability of transportation.

Because lithium is highly reactive, Li-ion batteries result in batteries of smaller size with comparable amount of energy when compared to competing battery technologies (lead-acid, nickel cadmium and Ni-MH batteries), (Sullivan and Gaines, 2012). Compared to nickel metal hydride batteries, Li-ion batteries are lighter, less bulky, and more energy efficient, have no memory effect, and a much lower self-discharging potential when not in use (Abell and Oppenheimer, 2009). Despite these advantages, lithium batteries have certain limitations. Thermal management is a challenge for the battery pack. Operating the batteries in high temperatures can limit the performance of the batteries and cause safety problems (Väyrynen and Salminen, 2012). Cost also poses a problem. Although future Li-ion battery costs are projected to significantly decrease with increased production volumes (Sullivan and Gaines, 2012), the current price is about $1,000 per kWh.

Li-ion batteries today use lithium in the form of Lithium Carbonate (Li_2CO_3) which is used to create the cathode material (1kg of lithium = 5.323kg of lithium carbonate). Discrepancy in estimates of the amount of lithium per battery exists (Tahil, 2010; Gaines and Cuena, 2000, Steinmetz and Shanker; 2008; Gaines and Nelson, 2009) and appears to be due primarily to differences in assumptions about battery requirements. This difference in estimates can be partially attributed to the fact that battery chemistry varies based on manufacturer design choices (USDOE, 2010). Gaines and Nelson (2009) estimated that a 100-mile range EV would require between 4.68 kg and 12.7 kg of lithium, depending on the lithium-ion chemistry used.

3. Methodology

This research uses an integrative literature review and SAM analysis to detail the different challenges faced by EVs with regard to supply of lithium and highlight the various risk areas. Furthermore, this study analyzes industry data from the literature to determine key issues and directions for future research. Various aspects of the global EV supply chain are considered and issues identified both from a global perspective as well as from a U.S perspective. An integrative literature review is used to provide an overarching framework to synthesize results (Torraco, 2005). The integrative literature review is especially useful in formulating an effective critique in new or emerging methods or developing a fresh perspective on an established topic. In this case, the methodology provides a solid structure for developing a supply chain system model capable of providing guidance in managing supply chain networks for electric vehicle battery technology.

SAM is a methodology that creates matrices in order to analyze and characterize research (Beruvides and Omachonu, 2001). In this paper, SAM is used as a tool to systematically analyze and classify data in various pertinent categories and to highlight the critical areas in lithium supply chain as well as to point out gaps in existing research. SAM analysis was chosen due to its flexibility allowing the methodology to be adapted to fit this study. The goal of this study is to provide a holistic analysis of issues related to lithium by including other factors that are underappreciated in current research but which have the potential to disrupt supply of lithium.

Sampling criteria were established to identify salient literature for the research. Initially, the scope was limited to only peer-reviewed scholarly publications and technical reports from 2001-2012. However, due to limited works available, the search was expanded to include older works to show the trend in the area. In addition, some relevant unpublished articles, particularly those cited multiple times within the accessed peer reviewed articles, were included in this study. Two key databases, ABI/Inform and Academic Search Complete, were used to conduct the search ABI/Inform was selected because it provides access to information in 1,000 business journals worldwide. Academic Search Complete is a multidisciplinary covering more than 8,600 full-text periodicals, including more than 7,500 peer-reviewed journals. Other databases searched include Business Source Premier, Academic Search Complete and Compendex. Keywords were used mainly in combinations to reveal literature linking lithium availability to supply chain issues. These keywords included lithium, electric vehicles, batteries, supply chain, lithium production, lithium supply, resource.

The initial criterion was to screen articles with an overall goal of finding a group of articles that focused specifically on lithium supply chain. Considering that lithium supply chain is an emerging field, a database search containing the keywords in the publication title, keywords and abstract fields did not return a significant number of journal articles. Therefore, to expand the results, we opted to search for the keywords in the 'all fields and text' field. Articles were selected or discarded based on their relevance to identifying key issues associated with supply chain elements of lithium and electric vehicle battery technology. Lithium is used in a wide variety of applications including industrial applications and in the healthcare industry and as such, several articles returned during the search addressed these fields and were not relevant to this research. These articles were identified and discarded after reading the abstracts. Also discarded were articles related to energy and chemistry that are outside the scope of this study. Full articles from the included abstracts were then examined further to determine if they met the inclusion criteria. Furthermore, the selected articles' reference lists were examined to identify additional relevant articles.

Presently an established format for conducting integrated literature review analysis does not exist (Torraco, 2005; Whittemore and Knafl, 2005). Some mathematical and statistical analysis (Charvet et al., 2008) can be conducted on bibliometric records. However, due to the limited number of sample articles, those analyses could not be applied to this study. Instead, this study used a quantitative and qualitative descriptive approach to synthesize research findings and detect common themes.

4. Results

4.1. SAM Summary

Forty-eight articles were identified and further screened for inclusion and exclusion criteria. Based on review of references of the 48 articles, an additional 11 articles were added and 15 articles were eliminated. Overall, 24 peer reviewed articles 9 reports, 4 conference proceedings and 7 non-journal articles were included in this review. There were no patterns detected in terms of journals that published the articles. Because this research focuses on lithium supply chain, particularly issues related to supply chain risks and disruptions, the literature were classified under six major components (see Table 1) including, lithium resource/reserve, supply, demand, geopolitical environment/trade partnering, cost and recycling. Table 2 shows varying degrees of the focus of the assessed literature on lithium availability, EV batteries and supply chain. It is important to note that research studies could focus on all three areas, but some focused on just one area. Due to the limited studies in this field, research that had tertiary and quaternary focus on lithium was included. In the following sections, we will discuss the state of the art in the literature related to the six components identified in the SAM.

Table 1. Summary of Articles by Topical Area

Breakdown by Major Areas									
	Author	Year	Type	Resource/ Reserves	Supply	Demand	Geopolitical Envr.	Cost	Recycling
1	Evans	1978	Journal	X					
2	Kunasz	1978	Journal		X	X			
3	Whistnant and Holman	1985	Conference Proceeding						
4	Evans	1986	Conference Proceeding	X					
5	Hammond	1988	Journal		X	X			
6	Nicholson and Evans	1998	Journal		X	X			
7	Vine	2000	Conference Proceeding	X		X			
8	Gaines and Cuenca	2000	Report					X	
9	Rade and Andersson	2001	Journal			X			
10	Andersson and Rade	2001	Journal		X	X			
11	Ebsenberger et al.	2005	Journal		X	X	X		
12	Fasel and Tran	2005	Journal		X	X			
13	Tahil	2006	Non-Journal	X	X	X		X	
14	Tahil	2008	Non-Journal	X	X	X	X		X

Table 1. Summary of Articles by Topical Area (Cont.)

15	Abell and Oppen heimer	2008	Report		X	X	X	X	X
16	Evans(a)	2008	Non-Journal	X					
17	Evans (b)	2008	Non-Journal	X					
18	Armand and Tarascon	2008	Non-Journal		X				
19	Steinmetz and Shanker	2008	Report		X			X	
20	Gaines & Nelson	2009	Report		X	X			
21	Yaksic and Tilton	2009	Journal	X	X			X	
22	Hopper	2009	Non-Journal				X		
23	Voelcker	2009	Report				X		
24	Beckdorf and Tilton	2009	Journal					X	
25	Dewulf et al.	2010	Journal						X
26	Power	2010	Non-Journal				X		
27	U.S. Geol. Survey	2010	Report	X	X				
28	U.S. Dept. of Energy	2010	Report		X	X		X	X
29	U.S. Dept. of Energy	2011	Report		X	X		X	X
30	Gruber and Medina	2011	Journal	X		X		X	
31	Boulanger et al.	2011	Conference Proceeding		X	X			
32	Wadia et al.	2011	Journal		X	X		X	
33	Bradshaw	2011	Journal		X	X			
34	Hensel	2011	Journal				X		
35	Farr	2011	Journal	X			X		
36	U.S. Geol. Survey	2011	Report	X	X				
37	Walker, Simon	2011	Journal				X		
38	Wanger	2011	Journal	X	X				X
39	Stamp et al.	2012	Journal	X					
40	Grosjean et al.	2012	Journal	X			X	X	
41	Kushnir and Bjorn	2012	Journal		X	X	X		
42	Ziemann et al.	2012	Journal	X	X	X			
43	Kesler et al.	2012	Journal	X					
44	Sullivan and Gaines	2012	Journal				X		
Total				**17**	**23**	**20**	**12**	**11**	**6**

Table 2. Focus of Reviewed Articles

Focus Area	Primary	Secondary	Tertiary	Quaternary
Lithium	24	4	4	2
EV batteries	3	6	4	6
Lithium/EV batteries	4	1	1	1
Supply Chain	2	0	1	0

4.2. Lithium Resources and Reserves

An accurate value for lithium reserves and resources is lacking (Fasel and Tran, 2005; Wadia et al., 2011; Andersson and Rade, 2001). Data are proprietary of a few companies and thus confidential. Some efforts were made early in the history of lithium use for industrial applications to calculate world lithium resources (Vine, 1976; Evans 1978; Evans 1986; Whistnant, 1985). Later on Nicholson and Evans (1998) assessed trends in the lithium market. However, neither reserves nor resources are a fixed estimate (Yaksic and Tilton, 2009) because this quantity changes as new deposits are discovered and new technologies are developed. The USGS has continuously increases its estimates for resources and reserves over the years due to re-evaluation as technology and other conditions change. For instance, the USGS increased its estimates of lithium resources from 25.5Mt (1Mt = 1 million tonnes) in 2009 to 33.7Mt in 2010 (USGS, 2010; USGS, 2011). Within that same period, USGS estimates of global lithium reserves increased from 9.9Mt in 2009 to 13Mt in 2010. These estimates were obtained from various sources including published research papers, unpublished reports, studies by government agencies, data from mining companies, trade journal articles among others. It is important to note that as technology advances, prices change and new information become available, the classification reserves or resources can change. For instance, if a major lithium producer reduces the price of lithium carbonate drastically, this action could render most other production uneconomic and, thus not reserves. The global distribution of lithium reserves (USGS estimate) are shown in Table 3 below.

Table 3. 2009/2010 World Lithium Mine Production and Reserves

Country	**Reserves (Tonnes)**	
	2009	**2010**
United States	38,000	38,000
Argentina	800,000	850,000
Australia	580,000	580,000
Brazil	190,000	64,000
Canada	180,000	—
Chile	7,500,000	7,500,000
China	540,000	3,500,000
Portugal	—	10,000
Zimbabwe	23,000	23,000
World total (rounded)	**9,900,000**	**13,000,000**

Source (USGS, 2011)

Lithium resource and reserve values show large discrepancy (Table 4). The studies assessed differ in their estimates partly due to fact that most deposits are estimated differently and most estimates of deposits do not comply with any internationally recognized standard (Gruber et al., 2011). Another reason for this disparity is because different numbers of estimates includes in the studies. For instance, Tahil (2007, 2008) and Evans (2008a, 2008b) included fewer deposits, thus leading to lower estimates compared to the other authors. Yaksic and Tilton (2009) point out that resource are of little use in estimating the long-term availability of mineral commodities because as reserves become depleted, the cost of extraction becomes prohibitive thus stopping mining/production.

Table 4. Recent Lithium Reserve and Resource Estimates

Reference	Li Resources	Li Reserves
	(Million Tonnes)	
USGS (2011)	33.7	13.0
Tahil (2008)	-	3.9
Evans (2008b)	29.9	-
Gruber et al. (2011)	38.7	19.3
Yaksic and Tilton(2009)	64.0	29.4

4.3. Supply and Demand

Currently no global market exists for lithium and it is not traded on the stock exchange. Prices for lithium have been obtained mainly from trade journals (USDOE, 2011). The evolution of lithium price is shown in Figure 2. The potential demand for lithium, particularly due to the growing popularity of electric vehicles has raised some concerns (Tahil, 2007, 2008). Brines, currently the cheapest source of lithium, are largely associated with salt lakes such as the Salar de Atacama and Salar de Uyuni. Only a few of hard rock mineral deposits of lithium exist in deposits that have economic value.

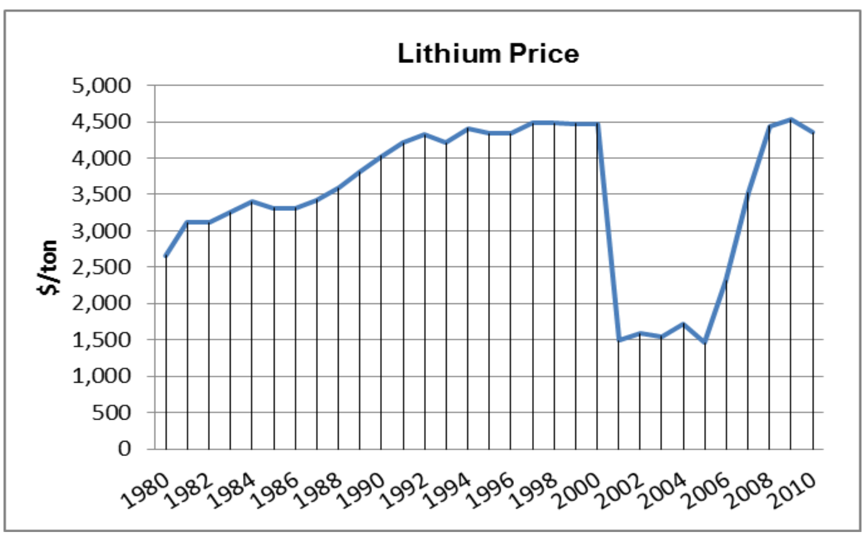

Figure 2. Evolution of Lithium Price: 1980-2010

Source: Kelly and Grecia (2011)

It is generally accepted that batteries especially for EVs will result in a significant increase in demand and represent a considerable share of the market (Bradshaw et al., 2011). An important area of concern is regarding infrastructure capacity: will production rates keep pace with rapid growth rate in demand? In the 70s Kunasz (1977) and Hammond (1977) assessed the ability of the lithium industry to satisfy the demands of automotive and storage batteries. Kunasz concluded that there was adequate supply to fulfill demand. Hammond, however, came to the conclusion that there was great uncertainty about the future of lithium due to lack of knowledge about the extent of resources. These studies were based on a lithium industrial structure that has since changed considerably. More recently, because of increasing use of lithium for industrial applications, various articles and reports have explored potential shortfalls in lithium production compared to expected demand (Boulanger et al. 2011, Tahil, 2008). Lithium supply is not simply based on the available material in the earth crust but also the ability of the available production infrastructure to physically increase production to meet the demand (Abell and Oppenheimer, 2009). As with the case of resource/reserve estimation, different techniques are used in the literature to assess the impact of rising demand for EVs on lithium production. Again, no two estimates are the same due to varying assumptions on some factors including lithium requirements for batteries, future EV battery ranges, different battery chemistries, production capacity and available reserves.

Using the cumulative availability curve, and assuming a worst case scenario in which demand for lithium for EV batteries rapidly increases over the coming decades, Yaksic and Tilton (2009) estimate lithium requirement between 2008 and 2100 to be 17.5Mt. This scenario includes an option to extract lithium from seawater at a cost of $7 -

$10 for each pound of lithium carbonate. In their model, Gruber et al. (2011) calculate the demand for EV Li-ion batteries, assuming that the batteries have 10 years of useful life and use approximately 0.114 kg Li per kWh. Seeking to calculate maximum expected lithium demand, their model uses a capacity requirement of 0.8 kWh, 20 kWh, and 60 kWh for HEVs, PHEVs, and BEVs batteries respectively. By their estimates, the upper limit for lithium demand from 2010 to 2100, including non-battery, portable battery and automotive battery uses are 19.6 Mt (with 12.8 MT from vehicle battery use).

Gaines and Nelson (2009) explore the demand for lithium if U.S. EV demand increases rapidly and then compare this to estimates of production and reserves to determine if there is a potential supply deficit. This study uses the most optimistic scenario for penetration of EVs in to the U.S. from a DOE Multipath Study (DOE 2007). Using this scenario, the authors assume that 90% of all light duty vehicles in the U.S are some form of EV by 2050. Based on their estimates lithium demand rises to over 50,000 tonnes annually by 2050 (assuming a NCA-graphite chemistry). Assuming world demand was four times U.S demand the authors estimate that current production levels will be sufficient to cover automotive demand (only) until after 2025. The automotive demand declines after 2035 if recycling is considered. It is important to note that this estimate considers only automotive demand and does not include portable battery and other non-battery demand. They conclude that "…even an aggressive program of vehicles with electric drive can be supported for decades with known supplies."

According to Wadia et al. (2011), for EV deployment based on annual production, nearly all lithium based couples have enough production to meet a short term target of (10-15yr) of 1 million 40kWh vehicle batteries, however a significant expansion of production capacity is required to meet the a long term goal (40-50yr) of 100 million lithium based EV batteries annually. Scale up will require a massive capital investment in mining and may require extraction of lower quality resources, driving extraction cost higher.

In contrast to other studies, Tahil's (2008) projection of lithium availability is alarming. His forecasts show that in an optimistic lithium production scenario combined with high non-automotive demand, only 30,000 tonnes of lithium carbonate will be left for automotive battery use in 2015. This amount, he estimates, is adequate for about approximately 1.3 million Chevrolet Volts (PHEVs). Under a more conservative scenario, less amount of lithium is available for EV applications. According to Tahil's estimation, lithium carbonate demand will exceed even the optimistic production scenario if demand in a high non-automotive scenario does not slow down after 2014.

Although there are conflicting reports on the quantity of lithium readily and economical recoverable, all agree there is enough lithium supply to last for the short-term. While some analysis (Gruber et al., 2011; Gaines and Nelson, 2010; Kesler et al., 2012) suggest that lithium availability will not constrain the growth of electric vehicles, conservative estimates of production levels by Tahil (2008) and Wanger (2011) indicate that lithium supply will lag demand by 2020 and 2025 respectively. Rade and Andersson (2001) argue the possibility that the use of metals in batteries could become a limiting factor in the expansion of EVs due to limited raw materials availability.

These limitations will be imposed based on various factors including battery life, recycling feasibility, metal scarcity, technology and metal requirement per battery. According to Waddia et al. (2011) and Gruber et al. (2011), scale up of lithium production will be particularly important to meet long term goals. Even less conservative estimates suggest that while lithium supplies will be adequate for vehicle demand, there is a risk of supply imbalances if EVs demand rises rapidly in a window of 10 to 20 years out (Mandel, 2010). The biggest hurdles, according to Gruber et al. (2011), to long term supply include increasing production capacity, advancing the mining technology and developing the Salar de Uyuni deposit.

4.4. Impact of Lithium price on Electric Vehicle Battery Cost

The price of lithium carbonate steadily decreased from about $6.50 per pound in 1954 to roughly $1.50 per pound in 1998 as South American production began. However, from 2003 the price of lithium carbonate increased reaching $2.80 per pound in 2008 (Yaksic and Tilton, 2009). Most recently in 2009, the price of lithium has further reduced by 25% (Gruber et al., 2011). In terms of cost, the authors assessed agree that a significant increase in lithium price will likely not have a major impact on the cost of batteries (Beckdorf and Tilton 2009, Yaksic and Tilton 2009; Wadia et al., 2011; Grosjean et al., 2012). This is due to the fact that the cost of the lithium in vehicle batteries represents a small contribution to total cost of production. Most of a battery's cost is in components besides the elements thus extraction cost of elements in active materials of several lithium based batteries are below $10 per kWh (Wadia et al., 2011).

4.5. Geopolitical Environment and Trade Partnering

It appears that the risks of geographic distribution are undervalued. Few articles addressed in detail concerns about the geographic distribution of lithium supplies and the implications for future supply. Research related to geopolitics though small is notable. In recent times, concerns surrounding energy security has influenced energy policies to focus more on EVs as energy efficient and sustainable solution to reduce consumption of petroleum, mainly produced in Middle East countries (Voelcker, 2009). Lithium is one of the strategic raw materials important to EVs (Korinek and Kim, 2011). In addition, the fact that lithium reserves are finite and concentrated geographically could lead to potential shortages in the future (Boulanger et al., 2011; Grosjean, 2012, Kushnir and Sanden, 2012).

The emergence of lithium as a strategic resource and the associated geopolitics is troubling (Voelcker, 2009). As China has demonstrated in recent years with rare earth elements, a major raw material for NiMH batteries, a country that supplies a resource can greatly affect the country that receives the resource. China, which controls over 95% of global rare earth elements supply, recently made a decision to restrict its export quota of this raw material (Hensel, 2011), causing a significant increase in prices. This action by China highlights the risks of global dependence. The greatest proportion of world lithium resources are located in South American countries including Chile, Argentina and Bolivia, which collectively account for about 60% of world resources. The principal share of known lithium reserves exists in China, Chile, Argentina, and Australia and together these regions were also responsible for over 90% of all lithium production in 2010 (excludes U.S. production). Despite being responsible for 12% of global lithium resources, U.S identified reserves is only 0.3% of the global total. Due to the very limited reserves, the U.S is likely to always be a lithium importer.

Some of the literature examined trade partnering and policy relationships with major lithium producers from a U.S perspective. Gaines and Nelson (2009) contend that the U.S has "…relatively stable relationships with major lithium-producing countries…", and therefore significant problems are not anticipated at the present time. However, some studies (Tahil 2007; Tahil 2008; Hensel, 2011; Walker, 2011) argue that the relationship between the U.S and some of the lithium supplying countries may change in the future. Hensel (2011) proposed that the development of alternative automotive technologies to reduce U.S. dependence on oil from foreign countries might result in trading dependence in one resource to dependence in another.

The U.S who is a very large consumer of lithium currently has minor output of lithium domestically, coming from the only active brine processing facility in Nevada and is heavily dependent on imports (Power, 2010; Walker, 2011). These imports are mainly from South American countries, which are responsible for 97% of U.S lithium imports. USGS data shows that in 2010, Chile produced 59% of the lithium imported into the United States, with the rest coming from Argentina (38%) and China (1%). As mentioned previously, this domination by South American countries has not always been the case. The United States was the leading global producer of lithium until 1997 when it was surpassed by Chilean operation. The U.S discontinued its role in mining because it could not compete with South American producers thus making production unprofitable. Consequently, the U.S shut down its mine in North Carolina that produced lithium minerals leaving the lithium brine production facility in Nevada. Hensel (2011) points out the striking similarity between rare earth sector and lithium sector in that the U.S previously had production operations in these sectors but shut down these facilities due to an inability to compete with foreign competitors. The low cost, large volume Chilean lithium producer, SQM, drove down market price by 50% thus forcing closure or limiting production of more expensive mining operations in countries like the U.S, China and Australia (Ebensperger et al., 2005)

Recently, China has set ambitious goals for the development of electric vehicles and battery technology (Levine, 2010). In addition, China consumes most lithium produced domestically (USDOE, 2010) Consequently, U.S. access to lithium produced by China may be limited considering that China is a likely competitor in the EV market and in the future China will prioritize its auto industry and therefore divert most of its lithium supply leaving little for export.

Also due to political instability, there is a question of U.S. access to materials produced in Bolivia, which holds the world's largest lithium resource. Despite having important resources, Bolivia is not among the top producers. Currently, Bolivia does not have any active lithium production facility but has new production projects in the pipeline. The Bolivian government is currently working to produce and manufacture lithium products that correspond with the growing demand for alternatively fueled vehicles (Farr, 2011). Due to Bolivia’s long history of resource exploitation by foreign countries, President Evo Morales has rejected advances of foreign companies demanding control of 60% of earnings (Power, 2010; Hopper, 2009). In addition, Morales, has a plan to mandate the development of facilities for Li-ion batteries and EVs to strengthen Bolivia’s economy. Due to a lack of foreign interests based on these conditions, Morales has independently begun development of a pilot plant. This may lead to limited lithium output from Bolivia in the future. Another obstacle is that the diplomatic relationships between the U.S and Bolivia deteriorated during the Morales administration, leading to the breakdown of key partnerships.

Although the U.S enjoys a close relationship with Chile, the existing Chilean mining law has restricted lithium concessions meaning that a significant increase in production is possible only through an amendment to the mining law. According to current Chilean legislation, only the Chilean government through its companies or special licensees by the President, can mine process and trade lithium (Ebensperger et al., 2005). This law excludes only those licenses granted before the law was passed. This law acts as obstacle to attraction of new lithium producers to the South American country.

Considering that oil prices are projected to rise in coming years, most lithium producing countries will likely make the shift to EVs especially as the EV battery technology matures and becomes more mainstream. This may mean more diversion of lithium production towards domestic uses thereby limiting exports. Tahil (2010) proposes that Chile and Argentina may have enough leverage to persuade foreign Li-ion battery manufacturers to invest in local production facilities in return for mining privileges.

4.6. Recycling

Recycling represents the least addressed area in articles assessed. This can be partly attributed to the fact that lithium recycling is in its infancy. There have been some recent efforts to promote recycling of EV batteries as this sector grows. However, current recycling programs focus mainly on avoiding improper disposal of hazardous battery materials and recovering battery materials such as cobalt and nickel that are considered more valuable than lithium (Dewulf et al., 2010).

5. Lithium Supply Chain Framework

The deployment of li-ion batteries for wide scale electric vehicle adoption could potentially create a vehicle system that is vulnerable to a wide variety of risk factors and barriers. Therefore, from a strategic standpoint, there is a strong case to carefully consider these issues. The supply chain in Figure 3 shows the various risk factors and constraints affecting the future of EVs. This model demonstrates the connection between supply and demand and provides a framework with which to investigate the technical, geopolitical and economic factors that impact the supply of lithium through the different life cycle stages. Thus the model can inform where to target both engineering management and policy actions.

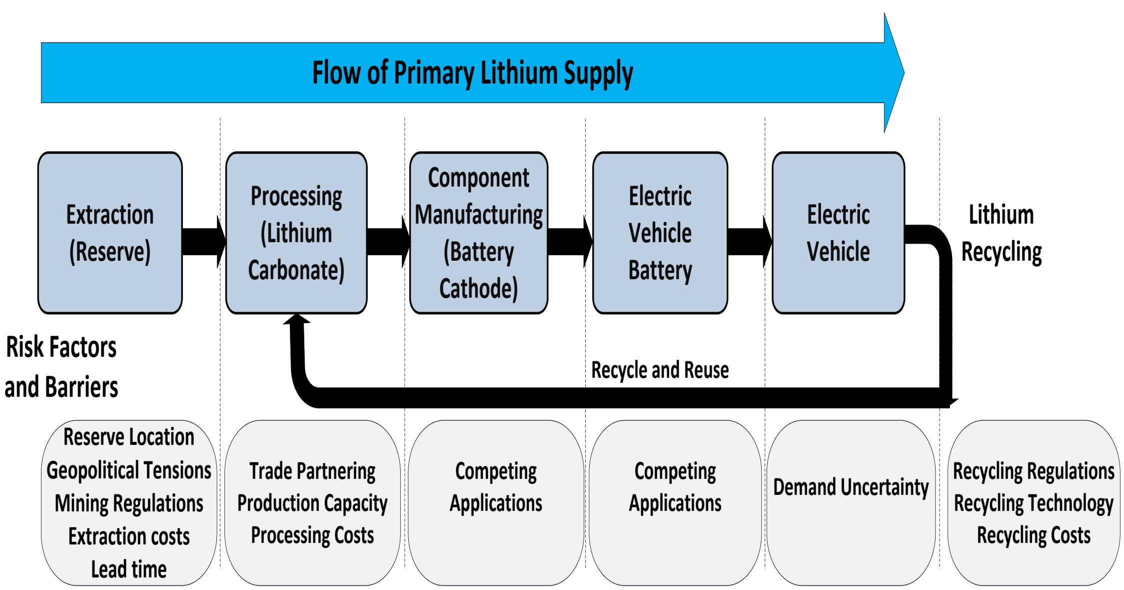

Figure 3. Lithium/EV Supply Chain Showing Risks Factors and Constraints.

At the mining or extraction stage, major risks include the location of the deposit, cost, geopolitical environment and mining regulations. These issues have a significant impact on lithium supply as they have the potential to disrupt supply even when lithium reserves are available. In the event of this disruption, the future of EVs may be jeopardized. These factors create complex relationships between the availability of lithium reserves and ability to supply the material when needed by technologies (in this case EVs) that use them. Furthermore, these risks may cause variations in supply curves that are not accounted for in most studies that focus on resource availability in the earth crust without considering institutional and other environmental aspects that could potentially be limiting factors.

Overall, this model indicates that some amount of skepticism is needed with regard to the material availability. Although several of these studies agree that there are adequate resources for the short to medium term, there is a potential for supply disruption if other factors are considered. For instance, lithium is more geographically concentrated than current oil supplies with roughly 90% of resources located in five countries. In addition, lithium production is heavily concentrated in four countries, which represent over 90% of current global production.

A potential risk is the influence of extraction cost on the readily available lithium supplies. The current producers can exert market power by keeping the price low and therefore limiting market entrance for other producers that may have less economic reserves. This was the case when production shifted from the U.S. to South America where production was cheaper. This limits diversity of supplies and increases the risk of supply disruption in the event that supplies from a major producer become unavailable. Therefore, it is crucial that engineering managers advance their knowledge about the complex relationships between these factors and lithium.

Currently, a battery technology that can compete with lithium for electric vehicle batteries does not exist and this is unlikely to change in the foreseeable future (Kushnir and Sanden, 2012). Although lithium demand for automotive batteries will grow significantly in the future, other end use applications will also have a considerable demand for lithium. After extraction, processed lithium is used to manufacture the cathode, which is a component in Li-ion batteries. At this stage, competing applications pose a risk to future EV deployment especially if there are no alternative lithium supplies and if alternative vehicle technologies are not developed. Rapid increases in demand could cause supply-demand mismatches and result in high prices with implications for lead time. The evaporation processes used for lithium extraction from brine can last for 12 to 18 months (USDOE, 2010). In the event of supply imbalances, the lead time with respect to lithium supply from brine may not be elastic enough to meet demand in a timely manner. In addition, there is no fast way to meet demand if the demand exceeds the production capacity as new processing facilities take about two years to be constructed (Kushnir and Sanden, 2012). If the high prices make it more economical to bring new mining operations online; this process could take several years for permitting and construction to take place. This means that supply response to scarcity may be slow, therefore, hindering lithium dependent technologies like EVs.

The supply chain also shows the potential for recycling and reusing lithium carbonate from finished applications. If recovered or secondary lithium is reused in production, the raw material requirement can be significantly reduced. However, at present, lithium recycling is almost non-existent. In addition, it is unknown if secondary lithium has a high enough quality for reuse in high-tech applications such as EV batteries

(Ziemann et al., 2012). Although, several studies assume that recycling will play a major part in EV future, this is not guaranteed. Recycling will be largely determined by factors such as recycling cost, recycling policies and recycling technology. These will influence the recycling feasibility, recycling efficiency and the collection efficiency of used end products. Assuming recycling economics and technology do not pose a threat and policies are in place then it is possible lithium recycling efficiency could reach 95% as is the case with lead acid batteries.

To proactively address these risks identified several approaches need to be taken. One response will be to develop and maintain diverse lithium supplies to minimize the risk of supply-demand imbalances and avoid long lead times. Developing alternative battery and transportation technologies would also reduce the risk of an over demand. Finally, it is crucial to implement strong policies to promote recycling and recover as much secondary lithium as possible.

6. Implications and Conclusion

The growth in demand for lithium based batteries together with the recent interests and growth in Li-ion battery powered EVs have raised concerns about the adequacy of lithium resources to meet demand. This research identifies the critical areas in the supply chain of lithium for EV battery manufacture including production capacity, recycling and trade partnering and geopolitical environment. Based on our analysis, it is evident that a lithium battery powered future is faced with not only the issue of resource availability but also includes the aforementioned issues. Scarcity of lithium will pose a considerable risk to the supply of EVs due to the fact that lithium resources are not equitably located.

Supply chain management is an important aspect of engineering management. Therefore, an engineering manager must be aware of issues that might adversely impact a supply chain. Lithium use will undoubtedly increase significantly in the future, therefore, it is important to take a proactive approach to understand and address some of these issues facing the supply chain. Otherwise there is a risk of trading dependence on oil for material dependence in the transportation sector. Failure to address these problems could cause supply chain disruption in the future and impact the future of the EV market. This is due to the fact that as the demand for lithium increases so does its criticality. These issues need to be dealt with in order for a lithium based EV industry to be sustainable.

The process of identifying all pertinent issues related to supply chain vulnerability is critical. The supply chain model in this study provides important information to the engineering manager on risk factors affecting lithium availability for EVs. The factors that pose a problem for lithium supply include the geographic location of deposits, geopolitical environment, demand of competing application and reactive production and supply capacity. In addition the model shows the stages in the lithium life cycle these risks occur. As lithium becomes more and more important to the EV industry it is critical to understand, manage, and mitigate those uncertainties and risks in the supply chain in a smarter, more informed way. As mentioned previously the risks identified in this study can be mitigated by maintaining a diverse lithium stock, developing alternatives and recycling.

Partnerships are also key to securing lithium supplies because lithium is concentrated in a few locations. Governments and automakers need to build strategic alliances with lithium producers and lithium producing countries to secure the lithium needed for EV batteries. Such alliances could increase stakeholders, reduce competition and minimize supply chain risk in the event of a rapid increase in demand.

This study shows the need for further analysis to examine the adequacy of lithium for EV battery applications. Data on raw materials is always subject to a degree of uncertainty because most of the information are estimates and are mainly available from second hand sources. This is problematic as there is no consensus in the literature regarding lithium resources and reserves as well as lithium supply to match demand in the future. While most authors agree that the current and planned production will sustain lithium demand in the short term, there appears to be some concern regarding long term supply and demand. Therefore, it is crucial that production capacity is reactive to avoid significant supply-demand mismatch and to meet long term demand. Our analysis indicates that very little research has been devoted to comprehensively assess issues that may arise because of increased lithium demand especially geopolitical and trade partnering issues. A major scale up of Li-ion batteries for EVs will require the establishment of new supply chains, which will have social as well as political impacts. Therefore, further study is required in order to achieve long-term energy and environmental goals. More research is needed to address and fully understand potential sociopolitical risks and bottlenecks due to the location of lithium resources, which could result in price volatility and supply chain disruption. Furthermore, work is needed to examine recycling and determine how much lithium can be recovered using current and future processes.

Significant deposits of lithium have recently been discovered in Afghanistan. The potential of these deposits could be impacted by the fact that Afghanistan has no mining industry and infrastructure and will likely require years to develop these resources. Another major issue to be considered is the fact that Afghanistan is presently one of the most political unstable regions in the world. In the future, research may be extended to examine how these deposits and other new discoveries will impact the global supply chain of lithium and the EV industry.

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III. A BIBLIOMETRIC ANALYSIS OF ELECTRIC VEHICLE RESEARCH: EVALUATING THE TECHNOLOGY AND THE ROLE OF POLICY

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Abstract

Widespread use of electric vehicles (EVs)—including hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs)—could reform the transportation sector and reduce dependence on fossil fuels. In recent years, the development of EVs has taken on an accelerated pace. Given the magnitude of knowledge produced, an assessment of the state of art could benefit the development of this area of study. This paper uses a bibliometric methodology to study trends of EV research. This analysis will provide insights on the status of EV research, the multi-disciplinary nature of EV study as well as identify emerging trends. Furthermore, this study makes some policy and research proposals to help the advancement of this technology. Results of this research will provide both engineers and policy makers with a better understanding of how various streams of research related to EVs are developing.

Keywords: Electric Vehicle, Bibliometric Analysis

1. Introduction

The transportation sector accounts for about 27% of global energy demand; most of this energy is supplied by fossil fuels particularly gasoline [1]. CO_2 emissions associated with the transport sector are expected to grow significantly in coming years. Therefore, a major challenge facing the transportation sector is developing innovative and affordable transportation technologies that meet the current vehicle technology performance but does not rely on fossil fuels [2]. Electric Vehicles (EVs) are a viable near-term transportation technology capable of addressing some of these problems facing the transportation system. Currently, internal combustion engine vehicles are the most prevalent transportation technology available and have dominated the transportation sector for almost a century.

Due to increasing concerns related to both energy conservation and environmental protection, the development of EVs has taken on an accelerated pace [3]. Although EVs currently represent a very small proportion of the total number of vehicles in most countries and territories, they are expected to experience rapid growth over the coming decades. Widespread use of EVs—including hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs)—could drastically reduce the dependence on fossil fuels, increase energy security and decrease the environmental footprint of the transportation sector. Many governments all over the world are also introducing policies to stimulate the advancement of the EV technology. For example, through legislations such as the Energy Independence and Security Act (EISA) of 2007, the American Recovery and Reinvestment Act (ARRA) of 2009, and other policies, the United States government is aggressively pursuing the advancement of EV innovation particularly PHEVs and BEV that have very limited market shares.

Given both the potential for EVs as the vehicles of choice for sustainable transport and the magnitude of knowledge produced in the field, an assessment of the state of art could benefit the development of the area of study. This paper examines the status of the EV technology including HEV, PHEV and BEV. First, we use a bibliometric methodology to highlight trends of EV research and analyze citation relationships. Secondly, we propose some policy and research recommendations to help the advancement of this technology.

Bibliometric analysis, a research method used to evaluate research performance, has existed for decades and has been employed in a variety of disciplines and topics [4] - [9]. More specifically, this method uses quantitative analysis to describe patterns of publication on a given topic. A close examination of research literature provides insight to researchers on publication output of a given topic including previous, current, and future research trends.

Few authors have used bibliometric techniques to study certain areas of EV technology. These studies, however, were based on EV related patents. Wang and Duan [10] used patent information to conduct bibliometric analysis on core EV technology structure. In [9] patent information was used to conduct bibliometric analysis on the regulatory change in the EV industry. In addition, [11] performed an analysis of the technology trends of fuel cell electric vehicles using a patent database. To the best of the authors' knowledge, no published bibliometric analysis of research literature on EV technology exists. Therefore, this paper aims to fill a gap in EV related literature by applying a bibliometric analysis to a representative collection of journal articles. Studying the structure of EV literature will provide insights on the past trends, the status, and the multi-disciplinary nature of EV research, as well as the identification of emerging trends. This study provides insights into the quantity and quality of research on EVs by analyzing the SciVerse Scopus database. Results of this research will provide both engineers and policy makers with a better understanding of how various streams of research related to EVs are developing.

2. Methods

According to [12], technology development and innovation diffusion follow an S-shaped pattern. This S curve is characterized by a slow initial progress, then rapid growth and finally a leveling off during market dominance [2], [12]. Recently, [2] assessed fuel cell vehicle innovation within the framework of Roger's innovation diffusion curve and proposed policy actions to accelerate the technology along this curve. In this study, the focus is on EV innovation. We use a bibliometric methodology to identify trends in EV innovation and propose policy directions that will advance EVs along this curve.

All documents used in this study were accessed from the online database, SciVerse Scopus. SciVerse Scopus is a citation database of peer-reviewed literature containing 46 million records. For this study, we chose to use only journal articles. These articles were chosen because they are considered 'certified knowledge', having passed through the critical review of fellow researchers [13]. In this study, the trend of annual publication output was determined mainly for articles published between 2000 and 2011 in order to shed light on EV trends and contribution within the aforementioned period. Furthermore, analysis was performed for 4-year sub-periods within this 12-year time span. The database was systematically searched for EV related papers published between 2000 and 2011 using the search words “electric vehicle” and “electric car” in the article title, abstract, and keywords field. Therefore, any records containing these words were returned in the results.

Documents were analyzed according to trends of publication output, subject category, journal pattern, country of publication, author-generated key words, and number of times cited. Citation analysis was based primarily on the impact factor, as reported by the Journal Citation Reports (JCR), and the number of citations per publication. Citation analysis was based on the assumption that authors cite papers that have the greatest impact on the EV field. Therefore, frequently cited papers likely have greater influence than less cited papers. This analysis will shed more light on the rate of progress in the EV research, the geographic distribution of publications and the areas of major focus.

3. Results and Discussion

3.1. Trends of publication output.

The original literature search resulted in 3392 EV related articles published between 1960 and 20011; 2,445 of these articles were published between 2000 and 2011. Between 2000 and 2011, the number of articles published annually grew from 106 in 2000 to 565 in 2011. Figure 1 illustrates the increasing trend of publications related to electric vehicles during the last half century. The growth in interest in EV technology overtime seems to follow Roger’s description of the S curve that is typical of technological innovation. Between 1960 and 1964, the curve remains relatively flat.

From the graph, it appears that EV research gained momentum during the 90's. This corresponds with the introduction of several legislative and regulatory actions in the United States and worldwide that targeted alternative fuel vehicle (AFV) development efforts. One such legislation is the California Air Resources Board's (CARB) zero-emission vehicle (ZEV) legislation.

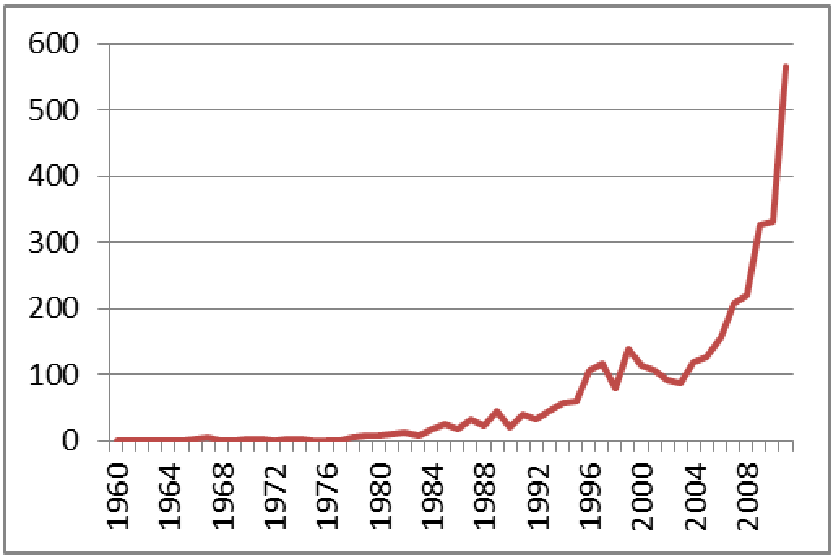

Figure 1. Annual Publication Output

(Total publications: 3392)

According to [9], the California ZEV mandate was the most evident regulation prior to 2002 to prompt an increased focus on electric vehicles. This legislation, introduced to lower emissions, stipulated that manufactures selling over 35,000 vehicles in California should have 2% of their sales made up of ZEV during 1998. This legislation has been revised since then. Because of this legislation a significant number of BEVs were introduce in the United States. This legislation also prompted an increase in research and development (R&D) efforts in the United States and other countries.

A significant rise in publications can be observed between 2010 and 2011, this coincides with increased focus on EVs as concerns about energy security, and environmental pollution grows. During this period EV research have received the greatest amount of funding compared to any other period. One significant source of funding for EV research is from the ARRA of 2009, which allocated massive funds for EV R&D. The lag in time is due to the time taken for the increase in funding to translate to an increase in publication output. Note that EV research levels off between 2009 and 2010; this may be attributed to reduced funding for EV research during the financial crises of 2008. Again, the lag in time can be explained by the fact that it takes some time before these changes in funding reflect on publication output.

3.2. Distribution by country and affiliation.

The 2,445 articles published between 2011 and 2011 accessed were spread across more than 65 countries. Figure 2 displays the top 15 countries with the most publications during this period. These results reflect that major industrial countries, which have increased interests and policies toward AFVs and EVs such as the United States, China, Japan, South Korea, United Kingdom, France and Germany, published the most articles. The top three countries with the most publications, including the United States (roughly

30% of the papers), China (13%) and Japan (11%), constituted over 50% of all publications.

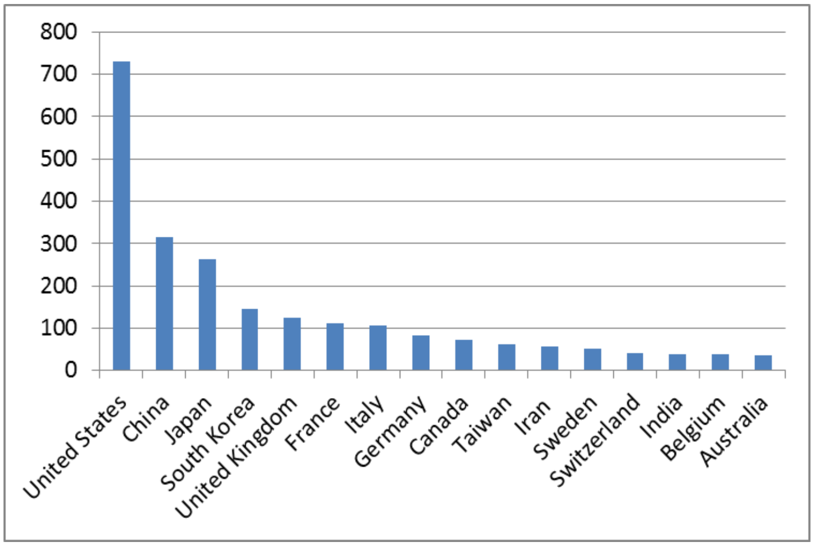

Figure 2. Distribution of Research by Country

The growth in EV research in the top five countries is shown in Figure 3 for the periods of 1990 to 2011. Since this study only examines articles in the English language some EV related research published in other languages are not included. Prior to 2000, neither Korea nor China had any significant EV research outputs, at least as reported in Scopus database. The United States, on the other hand, have had considerable research output over the period shown. Since 2000, however, China has overtaken Japan, Korea and the United Kingdom, in terms of academic research output. This growth in the Chinese output is likely due to the success of the 10th Five-Year Plan introduced in 2001 in China and provided policy support for EV research.

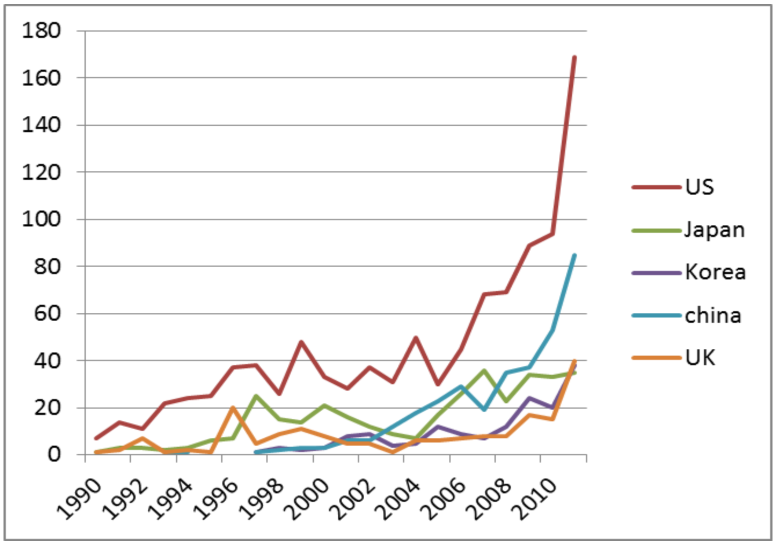

Figure 3. Top 5 Countries Publishing EV Research

The top affiliations of authors of academic articles can be seen in Table 1. The table shows that the most productive institutions are primarily universities. The top four author affiliations were the Beijing Institute of Technology (2.3% of the papers), Argonne National Laboratory (2.2%), General Motors (2.1%) and the University of Tokyo (1.9%).

Table 1. Distribution of Research by Institution

Institution	NP	%
Beijing Institute of Technology (China)	56	2.3
Argonne National Laboratory (United States)	55	2.2
General Motors (United States)	52	2.1
University of Tokyo (Japan)	47	1.9
Shanghai Jiaotong University (China)	45	1.8
Tsinghua University (China)	38	1.6
Illinois Institute of Technology (United States)	35	1.4
IEEE	29	1.2
Hanyang University (South Korea)	29	1.2
Vrije Universiteit Brussel (Belgium)	28	1.1
Ford Motor (United States)	28	1.1
Ohio State University (United States)	27	1.1

Table 1. Distribution of Research by Institution (Cont.)

Harbin Institute of Technology (China)	27	1.1
University Michigan Ann Arbor (United States)	26	1.1
The University of Hong Kong (China)	23	0.9
UC Berkeley (United States)	22	0.9

NP=Number of Publications

3.3. Distribution by journals.

Table 2 lists the top 22 journals publishing the most EV research and the corresponding percentage of papers accounted for by each journal over the 12-year period. The impact factor for each journal indexed in the 2010 edition of the JCR is also shown. The three most active journals were the Journal of Power Sources, the IEEE Transactions on Vehicular Technology, and the World Electric Vehicle Journal. During the period examined, these three journals published roughly 11.7%, 5.3%, and 4.8% of the total number of articles, respectively. Impact factors, if reported by the JCR, were provided for the journals. Of the top 22 journals, 17 had reported impact factors ranging from 0.36 to 4.29.

Table 2. Distribution by Source Title

Rank	Journal	NP	%	Impact Factor
1	Journal of Power Sources	286	11.70%	4.29
2	IEEE Transactions on Vehicular Technology	130	5.30%	1.49
3	World Electric Vehicle Journal	118	4.80%	-
4	IEEE Transactions on Industrial Electronics	59	2.40%	3.481
5	Energy Policy	58	2.40%	2.629
6	Journal of the Electrochemical Society	53	2.20%	2.427
7	IEEE Transactions on Industry Applications	43	1.80%	1.235
8	International Journal of Electric and Hybrid Vehicles	38	1.60%	-
9	IEEE Transactions on Power Electronics	36	1.50%	3.24
9	International Journal of Automotive Technology	36	1.50%	0.511
11	SAE International Journal of Engines	35	1.40%	-
12	Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering	33	1.30%	0.441
12	International Review of Electrical Engineering	33	1.30%	-

Table 2. Distribution by Source Title (Cont.)

12	International Journal of Hydrogen Energy	33	1.30%	4.057
15	IEEE Transactions on Energy Conversion	28	1.10%	2.489
16	IEEJ Transactions on Industry Applications	27	1.10%	-
17	Journal of Beijing Institute of Technology English Edition	25	1.00%	-
18	International Journal of Vehicle Design	24	1.00%	0.358
19	Electrochemica Acta	22	0.90%	3.65
19	Transportation Research Part D Transport and Environment	22	0.90%	1.108
19	Energy Conversion and Management	22	0.90%	2.072
22	High Technology Letters	21	0.86%	-

NP=Number of Publications

3.4. Distribution by subject category and keywords.

The 2445 articles studied were classified under 23 subject areas. Table 3 summarizes the top 10 subject areas. It is important to note that some articles are multidisciplinary and therefore classified under more than one subject. Engineering related articles accounted for the majority (>60%), followed by energy related publications at 31%. Table 4 summarizes the most frequently used author generated keywords. Not surprisingly, electric vehicles were the most commonly used keywords. Secondary batteries were the second most frequently used keyword. These papers addressed mostly the three most popular automotive batteries including lithium-ion (li-ion), nickel metal hydride, and lead acid. Some of areas addressed include load balancing, battery monitoring, and battery charging and discharging. Furthermore, results indicate that HEV technology is dominant in EV research growing from the fifth most used keyword in the 2000-2003 period to the second most frequently used keyword in the 2008-2011 sub-period. It appears that EV research in the past decade focused mainly on HEV technology and this is consistent with the fact that HEVs are the most widely available EV technology on the road. The top five keywords is rounded off by control technology, and electric motors, which represent the fourth and fifth most commonly, used keywords, in that order. Papers that provided control as a keyword addressed powertrain control, logic control, vector control, motor control, and fuzzy logic control among others. Papers that had motors as a keyword addressed electric motors, induction motors, motor control and more. Results indicate that papers published between 2008 and 2011, when compared to all other periods, had significantly more keywords related to plug-in hybrid electric vehicles. Also within this period was a considerable increase in the number of keywords related to the power grid. These papers focused primarily on the impact of EVs on the grid, smart grids, grid design, and vehicle-to-grid technology.

Table 3. Classification by Subject Area (2000-2011).

Engineering	1,564	64.0%
Energy	748	30.6%
Chemistry	479	19.6%
Materials Science	403	16.5%
Computer Science	325	13.3%
Physics and Astronomy	214	8.8%
Environmental Science	197	8.1%
Mathematics	150	6.1%
Social Sciences	97	4.0%
Chemical Engineering	76	3.1%

NP=Number of Publications

Table 4. Author Generated Keywords.

Keyword	**2000-2011** NP	**2008-2011** NP(R)	**2004-2007** NP(R)	**2000-2003** NP(R)
Electric Vehicles	911	612 (1)	208(1)	91(1)
Batteries	455	272(3)	125(2)	58(2)
Hybrid Electric Vehicle	445	306(2)	113(3)	26(5)
Controls	383	239(4)	101(4)	43(3)
Electric Motors	223	121(6)	66(6)	36(4)
Fuel cells	189	99(7)	76(5)	14(8)
Lithium	156	95(8)	40(8)	21(7)
Plug-in Hybrid Electric Vehicle	139	132(5)	7(14)	0(14)

Table 4. Author Generated Keywords (Cont.)

Drives	122	52(14)	48(7)	22(6)
Lithium ion Batteries	114	71(10)	33(9)	10(11)
Optimization	108	85(9)	15(12)	8(13)
Fuzzy Control/Fuzzy Logic	87	53(13)	22(11)	12(9)
Efficiency	87	50(15)	26(10)	11(10)
Emissions	81	59(12)	13(13)	9(12)
Grid	67	61(11)	6(15)	0(14))

R=Rank NP=Number of Publications

3.5. Most cited works in EV research.

The number of citations can be used to determine the quality of publications. The top 20 journal articles cited by English language journal articles and their relative citation frequencies during the 12 years covered by this study are presented in Table 5. The majority (12) of the top 20 most frequently cited publications are of United States origin. This suggests that the United States has higher relative influence compared to other countries publishing EV research. Typically, papers published at an earlier date have a receive more citations than papers published recently given that they have been in circulation longer. However, this was not the case. Thirty-five percent of articles in the top 20 were published within the latter half (2006-2011) of the study period. In fact, the top three cited journal papers were published in this period.

Table 5. Top Cited Papers in EV Research.

Rank	**Document Cited**	**2000-2011**	**2000-2003**		**2004-2007**		**2008-2011**	
		NC	NC	%	NC	%	NC	%
1	Chan et al. (2008)	519	0	0%	0	0%	519	100%
2	Kang and Ceder (2009)	282	0	0%	0	0%	282	100%
3	Kang et al. (2006)	234	0	0%	36	15%	198	85%
4	Endo et al. (2000)	139	28	20%	52	37%	59	42%
5	Xu et al. (2002)	121	14	12%	64	53%	43	36%
6	Klouz et al. (2002)	104	4	4%	56	54%	44	42%
7	Xiao and Zhou (2003)	103	1	1%	52	50%	50	49%
8	Meethong et al. (2007)	103	0	0%	1	1%	102	99%

Table 5. Top Cited Papers in EV Research. (Cont.)

9	Belharouak et al. (2003)	95	0	0%	51	54%	44	46%
10	Plett (2004)	88	0	0%	7	8%	81	92%
11	Lee et al. (2009)	87	0	0%	0	0%	87	100%
12	Kang et al. (2002)	82	2	2%	46	56%	34	41%
13	Zhang et al. (2001)	82	20	24%	39	48%	23	28%
14	Chan (2002)	81	1	1%	35	43%	45	56%
15	Chan et al. (2007)	80	0	0%	5	6%	75	94%
16	Kempton and Tomic (2005)	75	0	0%	5	7%	70	93%
17	Lin et al. (2003)	70	0	0%	14	20%	56	80%
18	Ogden et al. (2004)	69	3	4%	30	43%	36	52%
19	Moreno et al. (2006)	68		0%	5	7%	63	93%
20	Cacciola et al. (2001)	67	7	10%	29	43%	31	46%

NC=Number of citations

The majority of the articles studied addressed energy storage. More specifically, the focus of several of these papers was on either li-ion or other lithium-based batteries. This focus reflects the fact that energy storage remains one of the major challenges facing widespread EV adoption. The top three cited papers, [14]-[16], which had by far the greatest number of citations, represent a contribution to battery technology development.

Other articles that addressed topics other than battery technology maintained a high profile over the sample period. Some of these articles, such as [3] and [32] reported the state of art of the technology. Chan [3] provided an overview of the status of electric vehicles worldwide and their state of the art, emphasizing both the engineering philosophy and the key technologies. Cacciolla et al. [32] also reported the state of art on fuel cell technology, outlining the most significant results from all over the world. In [30] the concept of societal life cycle costing of AFVs is introduced.

The relative citation percentages shown in Table 5 reveal increase or decrease in influence or number of times cited during the three sub-periods. This provides an understanding of the changes that have taken place in EV research. The most discernible pattern was for articles to increase their influence in the third sub-period, from 2008-2011. This means that when compared to the other periods studied, most articles received the greatest number of citations in the period between 2008 and 2011. This trend suggests an increasingly growing impact of EV research in recent years. Some of these articles, however, were published more recently and, therefore, have only recent citations.

4. Policy and Research Recommendations

The evolving regulatory regime has prompted a focus on alternative vehicle technologies. Recent policies have encouraged the planning and development of EVs. However to sustain this growth in research output it is necessary to have continued policy measures to support development in this area otherwise the progress and momentum will be lost. In this section, we recommend some measures aimed at both researchers and policy makers to advance the growth of EVs along the S-curve.

One policy measure would be policies targeting various environmental goals to stimulate the development of EV technology. An example would be a policy focused on emission reduction. In addition, supportive policies are necessary to promote development and adoption of eco-innovations [33], [34]. For example the United States have various policies in place to support EV research and development and the impact of this increase in funding available for research has led to a significant increase in research output.

Although these government policies aimed at developing EV technology have resulted in an increase in research output, this does not necessarily translate to commercial success. Therefore, it is necessary for additional policies to focus on adoption and infrastructure in addition to continued development. Otherwise, the transition to EVs will be significantly limited. Adoption policies include both supply and demand side measures [34]. Supply side policies include technology-forcing regulations such as more stringent fuel efficiency. Demand side policies include financial incentives for early adopters.

Supportive policies that have proved effective in the past include subsidizing of the cost of technology purchase. The United States and Japan have for many years had subsides for HEV. More recently, the U.S federal government has also allocated funding for purchase of PHEV and BEVs up to a maximum of $7,500. This subsidy is critical in that it reduces the cost barrier, which is a major obstacle to the adoption of EVs. These policies are only intended to help the technology take off. Once there is a self-sustaining market for the EV technology then there will be no need for continued policy support. This is the case of HEVs in the U.S where the federal government discontinued subsidies once there was a functioning market for the technology. Therefore, these policies will be more beneficial for BEVs and PHEVs, which have not gained widespread adoption in the market. This subsidy together with increase in gasoline prices worldwide and EV technological advancement increases the attractiveness of EVs.

An additional policy to stimulate EV adoption would be imposing gas taxes to further increase the cost of gas prices. This policy will force people to choose more fuel efficient vehicles including EVs. Regional policies such as supplemental subsidies for purchase and infrastructure investments for charging that augment the benefits of federal EV policies are also important [35]. These policies will increase both adoption and research activity related to this technology.

Innovations such as EVs (mainly BEVs) are largely limited by fueling infrastructure. According to Browne et al. (2012), the lack of reliable charging infrastructure is complicated by the ‘chicken and egg’ conundrum. This is a situation occurs when customers are reluctant to purchase an AFV due to lack of refueling infrastructure, manufactures are unwilling to manufacture vehicle if there is no demand, the vehicle providers will not develop infrastructure since the demand is very low, and consumers cannot purchase the vehicles since there are unavailable [36] –[38]. This is a major obstacle facing the EV innovation. Therefore, it is crucial to develop policies that support adequate and reliable refueling and charging facilities. These policies should either directly support the development of EV infrastructure or facilitate the coordination between automakers and energy companies [34].

From this analysis, it appears that HEV technology is dominant compared to BEVs and HEVs. However, research related to both EV and PHEV is expected to increase significantly in the future due to the funding allocated specifically to these technologies. As research on BEVs and PHEVs grow, there will also be a need to increase research related to the power grid both from a national perspective but also from region specific perspective as the power infrastructure will be a major determinant of the success and sustainability of EVs. Energy storage remains a significant obstacle to the advancement of EV innovation and therefore, there is need for sustained research output in that area. It is important to direct funding on the aforementioned area in order to ensure that the EV technology is not stalled along the innovation curve.

5. Conclusions

A range of technology options is being aggressively explored to facilitate the transition to a more sustainable transport system. Near term, technologies such as EVs can provide sustainable mobility and help alleviate some of the problems created by conventional vehicle powered by fossil fuels. These vehicle technologies are beginning to penetrate the market; however, this analysis shows that there are still some significant hurdles facing EVs before they can be available in the mainstream market.

This paper uses a bibliometric methodology to explore EV research trends mainly in the period from 2000 to 2011 to quantify and address the structure of research literature in this area. This study provides a quantitative analysis of the state of art of EV and provides key information on areas of EV research; journals publishing the most EV research as well as identifying the most widely read authors and publications. The bibliometric methodology used in this study indicates that in the last decade there has been a renewed interest in EV technology. We find that HEV and EV battery technology are the dominant areas of research in the last decade. Research on PHEVs has also increased significantly in the last five years and with that there has also been an increase in publications related to the power grid.it is clear that the unites states is at this forefront of the EV technology in terms of academic research. Our results also show that China has been successful in not only catching up to but also overtaking Japan who was the established leader in the region. Our results also indicate that EVs have nearly made the move from a niche technology to commercialization.

6. Future work

This analysis scratches the surface of the potential that bibliometric analysis has for analyzing EV research. Future research will use co-citation analysis to provide relational links between most widely read authors, papers, and journals. Future work will also compare academic research with patent data to analyze relationships as well as to include institutions that do not publish results in academic journals.

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SECTION

2. CONCLUSIONS

This research investigated socio-technical issues facing the electric vehicle (EV) technology. Traditionally, engineers and policy makers take a divide and conquer approach in solving complex problems. This approach does not capture important interactions involved in EV adoption. Therefore, this study takes a socio-technical approach to address EV adoption in order to capture not just issues related to engineering and technology but also those issues that relate to environment, societal impacts, policy and economics.

The study of socio-technical barriers related to consumers is very important as this has a significant impact on the level of adoption of EVs. The sample used in this study provides helpful insights into attitudes of technology enthusiasts. Results of this research show that variations in preferences and attitudes towards EVs may be captured by differences in the characteristics of individuals, including age, gender and level of education. It appears that skepticism towards EVs detected in this group may be because these individuals are not yet convinced that EVs are comparable to conventional vehicles. In addition, several individuals in this group do not consider plug in hybrid electric vehicles and battery electric vehicles good for the environment because they are charged with electricity from power plants that use mainly fossil fuels.

Another major issue that affects EVs is the supply of lithium for EV batteries. The deployment of li-ion batteries for wide scale EV adoption could potentially create a vehicle system that is vulnerable to a wide variety of risk factors and barriers. Therefore, from a strategic standpoint, there is a strong case to carefully examine these issues. It is important to look beyond the availability of the material in the earth crust, as other risk factors have the potential to disrupt supply even when lithium reserves are available. These factors including, lead-time, competing applications, geopolitical regime and trade collaborating, create complex relationships between the availability of lithium reserves and ability to supply the material in a timely manner. These risks may cause variations in supply curves that are not accounted for in most studies that focus on resource availability in the earth crust without considering institutional and other environmental aspects that could potentially be limiting factors.

Based on the results of this research, it is important that some measures are implemented to support the development and sustainability of the EV technology. These measures, some of which are already being explored, include policies and programs to promote EV consumer adoption, advance EV research and development, and reduce supply chain risks of lithium needed for EV lithium-ion batteries.

Since almost all major car manufacturers are demonstrating interests in EVs and developing new passenger and commercial cars. The focus on automakers is to ensure that they take consumer concerns and perceptions into consideration when designing EVs. It is important that strategies regarding the future of development of EVs are continually informed from a consumer standpoint. This is because mismatches between consumer EV expectations and EV manufacturer goals, could potentially limit EV adoption.

EV manufacturers alone are incapable of a radical change in vehicle use and EV technology, therefore the government needs to support these initiatives. Based on the findings of this research and given the technological and economic problems facing EVs, the transition to EVs will be very slow without a profound modification of the public's perceptions of EVs. Therefore, there is a need to focus on communication and education aimed at modifying the public's attitudes and perceptions towards EVs. This measure together with other policy measures will help speed up adoption of the technology.

Regarding lithium supply for EV batteries, it is important to understand, manage, and mitigate those uncertainties and risks in the supply chain in a smarter, more informed way. This is because as lithium becomes more and more important to the EV industry, its criticality will increase. The risks identified in this study can be mitigated by maintaining a diverse lithium stock, developing alternatives and recycling. Furthermore, this study shows the need for further analysis to examine the adequacy of lithium for EV battery applications.

The importance of taking a socio-technical approach when studying EVs cannot be overemphasized because this approach considers the interdependencies within the system. This systems approach provides a comprehensive perspective thus exposing some risks that may be ignored otherwise. These risks, if unaddressed, have a potential to limit the widespread adoption of EVs even when technological problems have been resolved.

APPENDIX A

ELECTRIC VEHICLE CONSUMER SURVEY

1. What is your gender?		
Male	342	71%
Female	136	28%
Prefer not to say	3	1%
Total	481	100%
2. What ethnicity best describes you?		
White	408	85%
Native American/American Indian	2	0%
African-American	8	2%
Hispanic/Latino	4	1%
Asian	36	7%
Other, please specify	23	5%
Total	481	100%
3. What is your age (in years)?		
481 Responses		
4. What is your occupation?		
Student	385	80%
Faculty	52	11%
Other Missouri S&T Staff, please specify	44	9%
Total	481	100%
5. Please indicate your highest level of education (include degree you are currently working on)		
Elementary	0	0%
High school/GED	9	2%
Some college/Associates	69	14%
Undergraduate degree	247	51%
Masters	77	16%
PhD	74	15%

Post Doctorate	5	1%
Total	481	100%
6. Area of highest degree/major?		
481 Responses		
7. What is your annual family income from all sources before taxes?		
Under $25,000	108	22%
$25,000-$39,999	42	9%
$40,000-$49,999	28	6%
$50,000-$74,999	76	16%
$75,000-$99,999	56	12%
$100,000-$149,999	75	16%
over $150,000	21	4%
Prefer not to say	75	16%
Total	481	100%
8. Please describe in a few words what comes to your mind when you think about electric vehicles:		
481 Responses		
9. What type of electric vehicles or other vehicles that use alternative energy sources have you had experience with? Select all that apply.		
None	225	47%
Biofuel	67	14%
Hybrid Electric	184	38%
Plug-in Hybrid Electric	36	7%
Battery Electric	80	17%
Other, please specify	20	4%
10. How would you rate your interest in cars that use alternative energy sources?		
No interest	22	5%
Little interest	69	14%
Moderate interest	209	43%

High interest	181	38%
Total	481	100%
11. How would you rate your interest towards electric vehicles (EVs)?		
No interest	44	9%
Little interest	82	17%
Moderate interest	213	44%
High interest	142	30%
Total	481	100%
12. How likely would you be to consider purchasing a vehicle that uses alternative fuel?		
Not at all likely	73	15%
Somewhat likely	176	37%
Likely	123	26%
Very likely	109	23%
Total	481	100%
13. Which of the three electric vehicle types are you aware of? Please check all that apply.		
Hybrid electric vehicle (HEV)	455	95%
Plug-in hybrid electric vehicle (PHEV)	389	81%
Battery electric vehicle (BEV)	365	76%

14. Please rank the following EV types in terms of which appeals to you the most (1 being the most appealing and 3 being the least appealing) An ICE (internal combustion engine) is an engine used in most conventional cars in which combustion of fuel (usually gas and diesel) occurs A HEV (hybrid electric vehicle) adds a battery and electric motor to a car that uses internal combustion (IC) engine which is usually powered by gasoline or diesel. A PHEV (Plug-in Hybrid Electric Vehicle) uses HEV technology but its battery can be recharged via the electric grid, providing purely electric power for a limited range. A BEV (Battery electric vehicle) operates solely on an electric battery and also features a plug in charger			
Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.	**1**	**2**	**3**

HEV	208	128	145
	43%	27%	30%
PHEV	134	253	94
	28%	53%	20%
BEV	139	100	242
	29%	21%	50%

15. Please rank the following attributes of EVs in terms of which appeals to you the most (1 being the most appealing and 5 being the least appealing)

Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.	**1**	**2**	**3**	**4**	**5**
Decrease/eliminate the use of	183	92	52	63	64
petroleum	40%	20%	11%	14%	14%
Less maintenance	93	103	151	57	47
	21%	23%	33%	13%	10%
Reduced greenhouse gas	81	106	96	77	103
emissions	17%	23%	21%	17%	22%
Looks/style	50	71	70	101	165
	11%	16%	15%	22%	36%
Comfort	58	94	97	155	67
	12%	20%	21%	33%	14%

16. How many miles per day do you drive on average?

Less than 10	226	47%
11-20	117	24%
21-30	38	8%
31-40	37	8%
41-50	22	5%
Greater than 50	41	9%
Total	481	100%

17. As the size of an EV battery increases, the range increases, but so does the cost. With that in mind, how many miles minimum would the vehicle range have to be before you would consider buying a battery electric vehicle (BEV):

481 Responses		
18. What do you consider your biggest concern about EVs?		
High cost	129	27%
Battery range	158	33%
Safety	6	1%
Reliability	47	10%
Charging infrastructure	83	17%
Other, please specify	58	12%
Total	481	100%
19. How much ($/gallon) would gasoline have to cost to persuade you to drive an EV?		
481 Responses		
20. Do you consider charging an EV an inconvenience?		
Yes	177	37%
No	148	31%
Unsure	156	32%
Total	481	100%
21. "Quick-charging" refers to a higher voltage charging that is capable of charging your vehicle's battery in a shorter period of time than a standard wall outlet. If such chargers were available at public stations similar to gas pumps, how quickly would you expect your battery to be charged from empty to full?		
1-5 minutes	144	30%
5-10 minutes	185	38%
10-15 minutes	88	18%
Greater than 15 minutes	64	13%
Total	481	100%
22. EVs that are coming to the market today have warranties on their batteries of around 8-10 years. Knowing that batteries constitute a large portion of the cost of an EV, how concerned are you about the degradation or possible failure of your EV's battery.		
Very worried	205	43%
Somewhat worried	230	48%

Not worried	46	10%
Total	481	100%
23. Would you be more willing to purchase an EV if the ownership of the battery and the vehicle were separated such that you could purchase the vehicle without the battery for a lower price and instead pay for a monthly subscription, similar to a cell phone plan, which covers the cost of battery ownership and the price of recharging and/or swapping your battery?		
Yes	154	32%
No	120	25%
Unsure	207	43%
Total	481	100%
24. Do you like the idea of "battery swap stations" where your depleted battery could be swapped out and replaced with a fully charged battery in one minute?		
Yes	320	67%
No	63	13%
Unsure	98	20%
Total	481	100%
25. Do you have accessibility to an external electrical outlet to charge an EV where your car is parked at your primary residence?		
Yes	244	51%
No	237	49%
Total	481	100%
26. Electric vehicles are a safe mode of transportation		
Strongly agree	89	19%
Agree	188	39%
Neutral	120	25%
Disagree	26	5%
Strongly disagree	13	3%
Unsure	45	9%
Total	481	100%
27. Are you familiar with the term "sustainability"?		

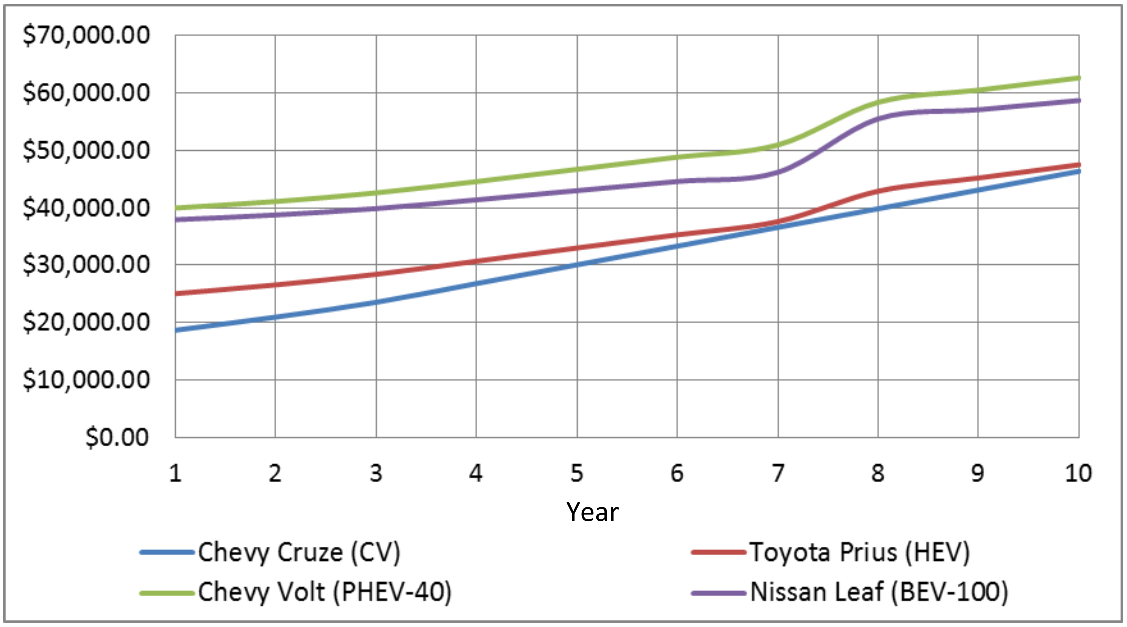
Yes		401	83%
No		80	17%
Total		481	100%
28. If you answered "yes" to question #27, what does sustainability mean to you? 380 Responses			
29. When purchasing a vehicle, does sustainability of the vehicle influence your decision?			
Yes		379	79%
No		102	21%
Total		481	100%
30. Electric vehicles are the most sustainable choice of personal transportation when compared with traditional gasoline-powered vehicles and other alternatives			
Strongly agree		32	7%
Agree		119	25%
Neutral		206	43%
Disagree		88	18%
Strongly disagree		36	7%
Total		481	100%
31. Rank the following types of electric vehicles in terms of which is a more environmentally sustainable mode of transportation. (1 being the most environmentally sustainable and 3 being the least environmentally sustainable)			
Top number is the count of respondents selecting the option. Bottom % is percent of the total respondents selecting the option.	**1**	**2**	**3**
Battery Electric Vehicle	220	94	167
	46%	20%	35%
Hybrid Electric Vehicle	126	148	207
	26%	31%	43%
Plug-in Hybrid Electric Vehicle	135	239	107

	28%	50%	22%
32. What, if anything, could be done to make you want to purchase an EV?			
336 Responses			
33. What questions, if any, do you have about electric vehicles and alternative energy vehicles, in general?			
175 Responses			

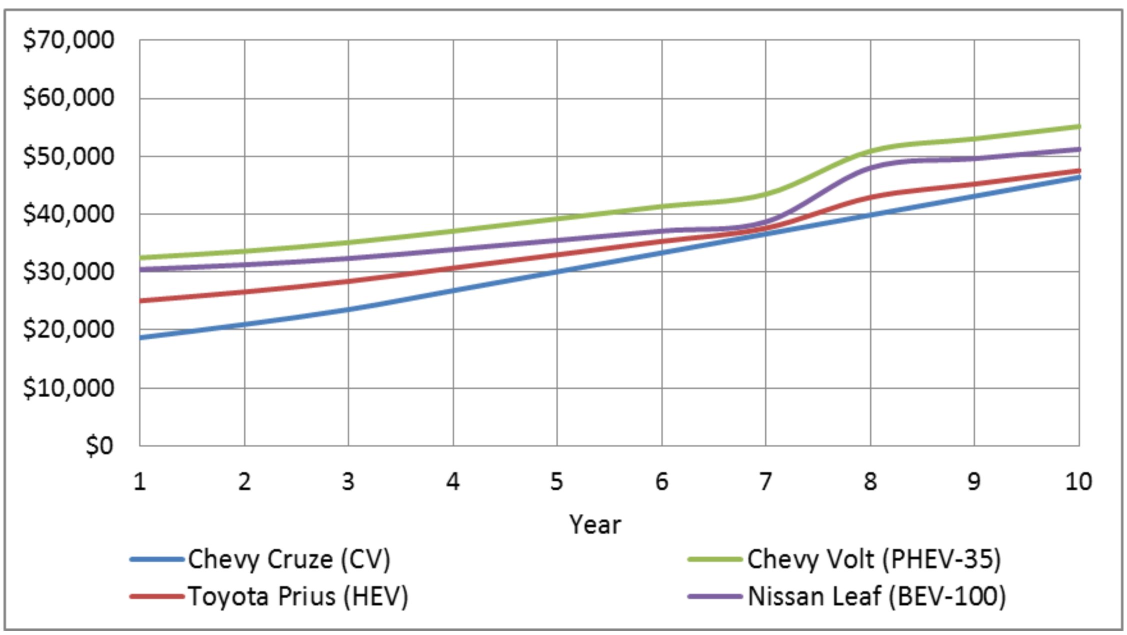
APPENDIX B

10-YEAR VEHICLE COST OF OWNERSHIP RESULTS

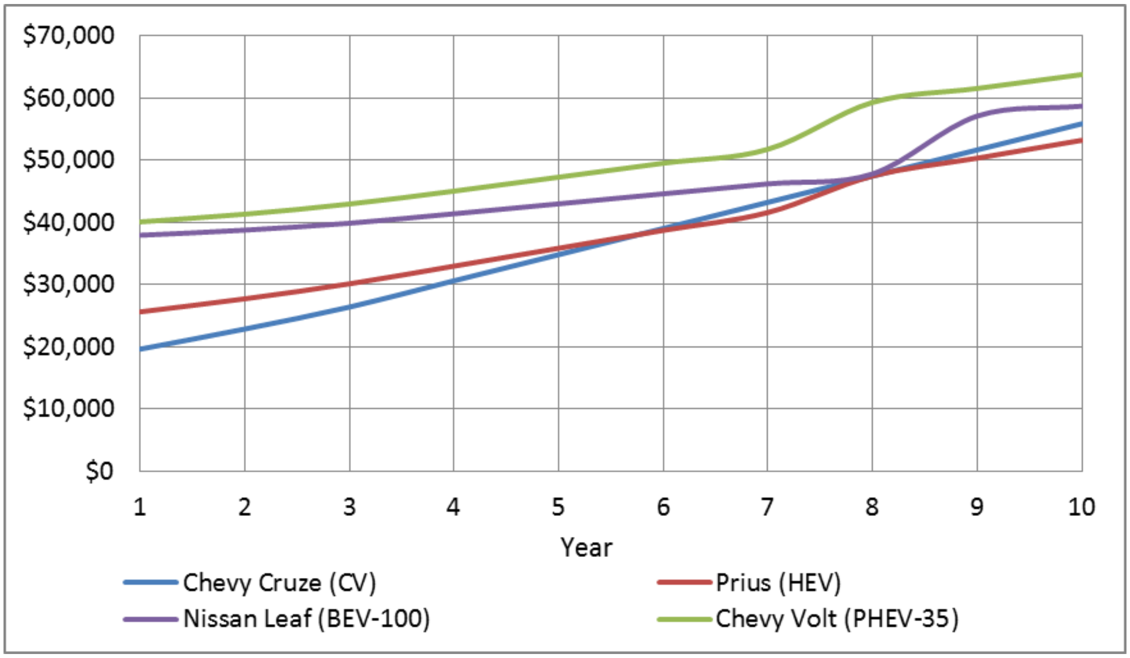
10-Year Vehicle Cost of Ownership at $3.5 per Gallon of Gasoline without American Recovery and Reinvestment Act (ARRA) 2009 Incentive



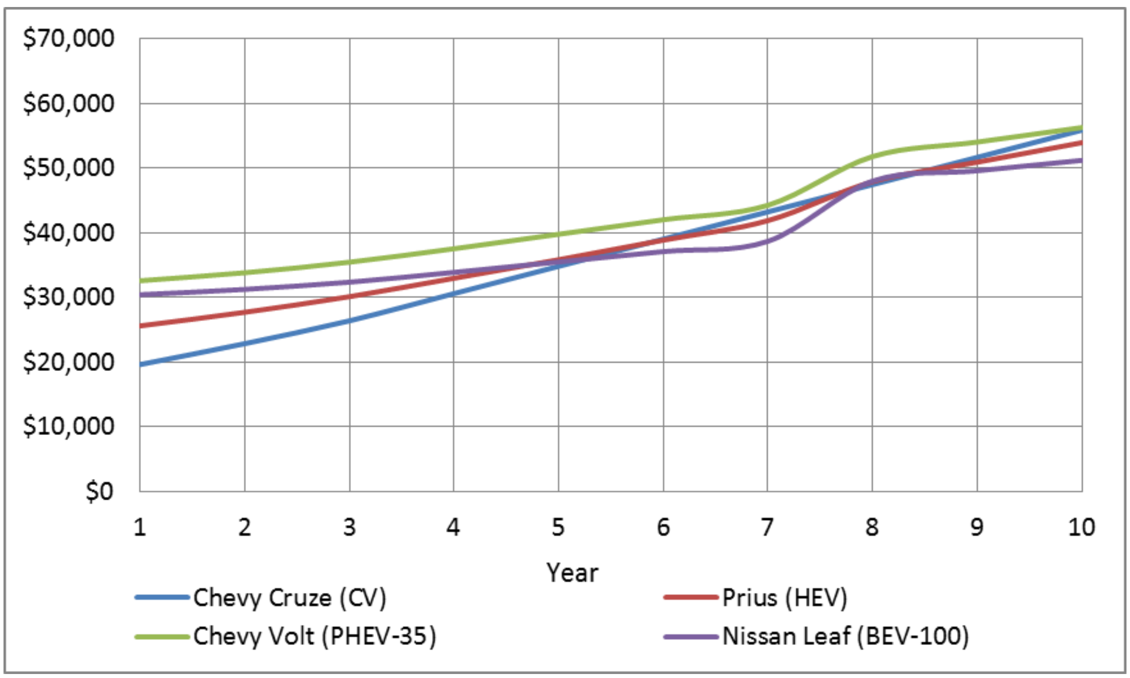
10-Year Vehicle Cost of Ownership at $3.5 per Gallon of Gasoline with ARRA Incentive



10-Year Vehicle Cost of Ownership at $5.42 per Gallon of Gasoline without ARRA Incentive



10-Year Vehicle Cost of Ownership at $5.42 per Gallon of Gasoline with ARRA Incentive



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VITA

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