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RESEARCH ARTICLE

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Techno-economic analysis of the adoption of electric vehicles

Abstract Significant advances in battery technology are creating a viable marketspace for battery powered passenger vehicles. Climate change and concerns over reliable supplies of hydrocarbons are aiding in the focus on electric vehicles. Consumers can be influenced by marketing and emotion resulting in behaviors that may not be in line with their stated objectives. Although sales of electric vehicles are accelerating, it may not be clear that purchasing an electric vehicle is advantageous from an economic or environmental perspective. A techno-economic analysis of electric vehicles comparing them against hybrids, gasoline and diesel vehicles is presented. The results show that the complexity of electrical power supply, infrastructure requirements and full life cycle concerns show that electric vehicles have a place in the future but that ongoing improvements will be required for them to be clearly the best choice for a given situation.

Keywords BEV, battery powered electric vehicle, environmental impact of electric vehicles, techno-economic analysis, gasoline versus electric powered cars, diesel versus electric cars, consumer behaviour

1 Introduction

Battery powered electric vehicles have been a potential transportation choice for at least 180 years (Larson et al., 2014) but they have struggled to gain consumer interest. Technological advances in materials and combustion have continuously improved the attractiveness of the gasoline powered vehicle to maintain it as the clear market choice for most of the preceding century (Van Wee et al., 2000). A recent shift has been the commercial introduction of hybrid electric vehicles (hybrids) and plug-in hybrids which both have on-board fossil fuel optional power to reduce the required storage capacity of the batteries. The traditional challenges with battery powered electric vehicles center on the short range of the vehicle between charges along with long charging times (Kley et al., 2011) preventing wide adoption by the marketplace.

Times, however, are changing. In the past decade, improvements in battery weight and life have increased the viable distance for electric cars and they are now gaining market appeal. Climate change and questioning the continued reliance on hydrocarbons is providing fertile ground for a resurgence in electric cars and is developing interest in new battery technologies to increase range and decrease charging times. This is especially the case for automotive applications where technological advances are being sought to reduce local emissions and support developments such as self-driving and other autonomous operations. This interest is buoyed by higher costs and uncertain dependability of supply for fossil fuels, and the negative impact on air quality caused by vehicle traffic (Egbue and Long, 2012).

Purchasing a new car is typically the next major capital expenditure for individuals after housing and the decision is generally not taken lightly (Bernasek, 2002). However, consumers do not always act in a manner that would follow logical or even deductive reasoning. For instance, when comparing the costs of renting or owning a home, people are found to accept a lower standard when renting than when purchasing, so that renters appear to statistically pay less. This may not be the case when comparing similar living environments, in that owning may then be the lower cost option (Shiller, 2007). Applying this to vehicles, comparing the overall cost or environmental impact of new versus used or fuel type for vehicles is complicated by driver behavior associated with vehicle choice. A new more fuel efficient car may be driven more (including for pleasure trips) and therefore be more costly and impact the

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environment more than an inefficient vehicle that is seldom used. Furthermore, marketing can be effective in driving consumer choices, which may not be fully aligned with the consumer's stated objectives. As an example, Bastian et al. (2016) point out that a diesel car may be purchased with the premise of saving money, but the actual diesel vehicle purchased by the consumer tends to be larger and 50% more expensive than a gasoline model they would otherwise have selected. The increased size and typically higher at the pump fuel cost for the diesel does not justify the purchase of the diesel vehicle on a cost only basis, and particularly if the buyer is trading in a functional gasoline powered vehicle with many remaining years of service. In addition, recent revelations of misreported emissions has greatly tarnished the diesel car as an environmentally friendly alternative (Dadush, 2018).

Considering the ubiquitous nature of vehicles and the important role they play in personal finance, this paper seeks to shed light on the current increasing popularity of battery powered electric vehicles and help quantify the benefits and limitations on these vehicles. The paper explores the forces driving the increased interest in electric vehicles, the current technology and potential for improvements in the storage/use of the energy to power them, the human factors that influence decisions on electric vehicles, and finally the challenges and trends in the potential wide adoption of these vehicles. A summary of suggested areas of further research is then presented.

2 Techno-economic analysis (TEA) and framework

There are many interconnected factors that have the potential to impact the adoption of electric vehicles and these factors are influenced by both technological and economic developments. Therefore, this paper reports on our research that is based on TEA of the primary areas contributing to the adoption of battery powered electric vehicles.

TEA is a recognized technique to support the evaluation of economic feasibility or viability for a specific technological development, system, or product. For instance, TEA has been used to support the analysis of a hybrid solar-wind power generation system (Yang et al., 2009), biomass-to-liquids production based on gasification (Swanson et al., 2010), and the integration of hydrogen energy technology for renewable energy-based stand-alone power systems (Zoulias and Lymberopoulos, 2007).

Figure 1 provides a schematic view of the TEA deployed in this research study, which provides a holistic perspective of both the economic and technology related factors affecting the adoption of electric vehicles as well as analysis of data on the worldwide growth of electric vehicles.

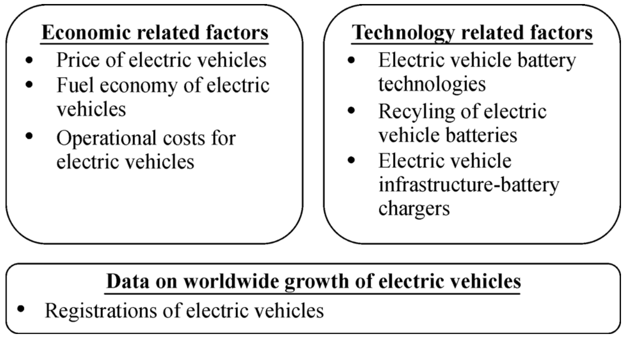

Fig. 1 TEA framework deployed in this research study.

3 Environmental considerations

As with many changes in technology and society, progress along a given path is not generally controlled by an overseeing authority. There may be changes in preference that do not align with the intentions of the users. The increased popularity of electric vehicles may be driven by perceptions that do not align with reality. A commonly held concept is that electric vehicles are environmentally 'better' without basing this idea on rigorous data. This section examines environmental factors from an in-depth review of the literature on the subject.

The use of plug-in electric vehicles offers a technological option to enable substantially lower levels of CO_2 emissions compared to combustion engine vehicles, thereby supporting reduced transport emissions without restricting personal car use (Graham-Rowe et al., 2012). That is, battery powered electric vehicles offer a potential for zero emission capability depending upon where they are manufactured and charged. When the electricity stored in the batteries or the energy used in manufacturing is generated from burning fossil fuels, the electric vehicle approach is not an overall zero-emission technology application. There are regions where the charging power comes from zero-emission sources (after the infrastructure is built) but no currently available vehicle would be manufactured without using fossil fuels for the components. Nevertheless, battery powered electric vehicles are becoming substantially more popular both in developed economy countries and emerging economy nations. The automotive industry and particularly the consumption of oil products as fuel has been a major target of criticism by groups interested in environmental issues (Avci et al., 2014). The focus of the criticism has typically been due to the emissions as a result of driving the vehicles, as opposed to the entire lifecycle impact including manufacture, delivery and disposal.

The Nissan Leaf is generally considered to be the first fully electric modern production vehicle, released in 2010 (Van Haaren, 2011). As with the case of diesel vehicles and as discussed above, the motivation for purchasing an electric vehicle may not be in alignment with the realized outcome. Many consumers have a belief that electric vehicles do not contribute to CO_2 emissions (Hofmann et al., 2016). The actual emissions associated with electric vehicles are complex, however, and are highly dependent upon the region in which they are built and driven since the source of electricity and other energy consumed in the product life cycle greatly influences their environmental impact. While electric vehicles can achieve zero tailpipe emissions, the environmental life cycle analysis suggests that it is not clear whether they create more or less emissions overall than a gasoline vehicle.

As noted earlier, the behavior of consumers is not always in line with their stated motivations. A review of consumers of electric cars in Norway (Klöckner et al., 2013) found that the electric cars purchased were generally intended by the customer to be used as a second car for short haul trips and did not contribute to any significant reduction in gasoline consumption by the owner. The motivation to purchase the electric vehicle may have been to save on gasoline, but the actual outcome does not support that intention. Organizations such as the Santa Barbara County Air Pollution Control District implement programs at various times to fund the decommissioning of older cars in order to promote the purchase of new, more environmentally friendly vehicles in their communities (Lucsko, 2014). One benefit of such programs is the reduction of environmental stressors in the geographical area where the driving takes place. The increased emissions associated with the production and distribution of the new vehicles are generally in another jurisdiction. The overall benefit of such programs would, therefore, be demonstrably higher if it could be shown that the overall net impact of scrapping the old car and replacing it with a new model resulted in lower net emissions. The net impact of such programs is hampered again by the behavior of the consumer. The amount of fuel consumed is the product of the consumption rate per unit distance and the total distance traveled. Much literature refers to the 'rebound effect' (e.g., Ajanovic et al., 2016), whereby new vehicles, and particularly those with increased efficiency and the resulting lower vehicle travel cost per unit distance, have the effect of increasing the annual distances traveled by the owners and thereby reduce or eliminate any economic or environmental benefits of upgrading. This increased traffic also increases infrastructure impacts due to increased road maintenance, congestion and accidents (Gerarden et al., 2017). The above examples are offered to show that deductive reasoning used to justify an action may not result in outcomes in line with the intentions. The Norwegian may have justified the new electric car purchase on saving gasoline and reducing emissions. The car replacement program was intended to improve environmental impacts. The actual outcomes suggest that the results do not match the intentions.

Another concern for widespread adoption of battery powered electric vehicles has been the fear of disposal by abandonment as is currently common with gasoline vehicles. This was particularly noted for lead based batteries and the possibility of contaminating soil (e.g., Socolow and Thomas, 1997). Lithium batteries from hand-held devices have traditionally gone to the landfill. From a general perspective the scrapping of the metallic materials from lithium-ion batteries requires the two main classes of recycling process, principally physical and chemical processing (Xu et al., 2008). Physical processing may involve pre-treatment processes, namely as skinning, removal of the crust, crushing and sieving as well as separation of the materials to ensure separation of the cathode materials from any other materials. Thereafter, the cathode materials separated are subjected to a series of chemical processes to remove the cobalt and other metals. There are clear incentives for recycling lithium-ion batteries and that this would result in an estimated saving of 50% of natural resources. This is not only from a decreased dependency on mineral ore but is also a consequence of reduced fossil resource (representing 45% reduction) and nuclear energy demand (representing 57% reduction) (Dewulf et al., 2010).

In terms of adopting recycling technologies, Gaines (2014) reports that a form of smelting based on pyrometallurgical recycling has been commercially deployed. In this process the electrolyte and plastics are burned to supply energy for the smelting, while the valuable metals are reduced to an alloy composed of copper, cobalt, nickel, and iron. Subsequently these metals are recovered from the alloy via a process of leaching. Moreover, the slag from the process contains lithium, aluminum, silicon, calcium, iron, and any manganese that is derived from the cathode material. This process is operating commercially for batteries with cathode materials that contain cobalt and nickel, but the process is not viable for newer battery designs, such as those that include manganese spinel cathodes. To illustrate the commercial case for this process, Fig. 2 includes the approximate

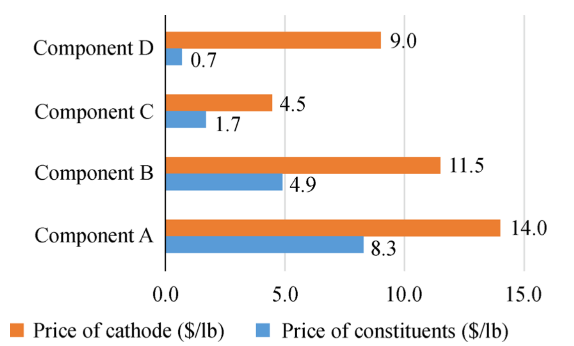

Fig. 2 Commercial case for recycling metallic materials from lithium-ion batteries (source of data: Gaines, 2014). Component A = $LiCoO_2$, Component B = $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$, Component C = $LiMnO_2$, Component D = $LiFePO_4$. Price of cathode values for Components A and B are based on average points from a data range.

cathode and elemental constituent financial values. When the cost of the component materials is high compared to the value of the cathode (such as with Component A) the viability of recycling is much greater than when the salvage value compared to the value of the cathode is much lower (Component D). Recycling of old batteries is easier to support when there is an economic case for doing so.

At present, it appears that the environmental impact or potential societal benefit of using electric vehicles is not as clear as many consumers would believe. Research into life cycle analysis of large scale adoption of electric vehicles is required to better determine if this technology will deliver the benefits many currently perceive to be there. This situation is complicated by the promise of improved technology around the performance of batteries and charging.

4 Technological challenges and potential for advancement

The challenges of battery powered electric vehicle adoption by consumers hinge mainly on the range, charging times, original cost and replacement cost of the batteries. The literature indicates that costs of battery technologies and the corresponding cost of battery powered electric vehicles are decreasing and this has been associated with technological learning (Weiss et al., 2012). Battery powered electric vehicles are expected to remain more expensive than hybrids. Battery powered electric vehicles are also likely to require sustained and major levels of investment in research, development and demonstration for costs to be driven down further (Catenacci et al., 2013). This position is also supported by a systematic review by Nykvist and Nilsson (2015). This work identified that cost estimates across the industry have decreased by about 14% from 2007 to 2014, corresponding to a reduction in the cost from above 1000 USD/kWh to around 410 USD/kWh for battery storage capacity. The study also identifies that manufacturers achieved a cost base of around 300 USD/kWh through annual reductions of 8%. However, Van Vliet et al. (2011) estimate battery powered electric vehicles will not be competitive with normal combustion engine vehicles until this cost drops to 170 USD/kWh. To give this perspective, the Nissan Leaf has a maximum power draw of 110 kW and a battery capacity of 40 kWh. This yields a reserve of 22 min at full power and a target battery cost of 6800 USD compared to the above 2007 cost of 40,000 USD. Consequently, the falling costs of lithium-ion battery packs pave the way for faster adoption of electric vehicles than was previously predicted, and eliminates the environmental concerns of lead.

Regarding battery types, lithium-ion based technologies are seen as having the most optimal set of capabilities across specific energy, specific power, efficiency, cycle life, lifetime, safety and costs (Gerssen-Gondelach and Faaij, 2012), although further technological development is still required to achieve commercially robust levels of performance across all the areas. Moreover, production of lithium battery technology largely rests on the manufacture of a graphite anode with a lithium cobalt oxide cathode and a liquid solution of a lithium salt (e.g., LiPF6) in an organic solvent mixture (Scrosati and Garche, 2010).

Lithium-ion batteries represent the leading technology option for electric vehicles offering high energy and power densities, but availability of world lithium resources also needs to be considered. While it is estimated that current usage levels can be readily met, it is possible that as electric vehicles become more widespread, the greater demand for such batteries will place severe pressure on lithium reserves. In terms of lithium products available in the market, there are a number of mineral and other commercial forms as depicted in Fig. 3 (Grosjean et al., 2012). This highlights that lithium carbonate (Li_2CO_3), mineral concentrates and lithium hydroxide (LiOH) are the most common commercial forms of lithium representing approximately 80% of the market. According to Grosjean et al. (2012), in 2007 the main applications were in ceramics and glass industries with 37% of the market share versus 20% for batteries. This split of lithium usage will change as demand for lithium-ion batteries increases.

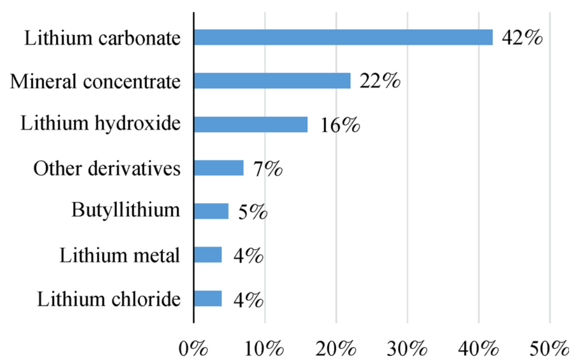

Fig. 3 Market shares of lithium-based commercial products (source of data: Grosjean et al., 2012).

There is currently extensive research being performed on many aspects of lithium-ion batteries. For example, this includes the lithium-ion battery graphite solid electrolyte interphase (SEI) and the relationship with formation cycling (An et al., 2016) and on interconnected silicon hollow nanospheres for lithium-ion battery anodes in regard to long cycle life (Yao et al., 2011). Indeed such research avenues need to be encouraged and funded in order to collectively reduce the technological risks of large-scale lithium-ion battery use in electric vehicles. The utility of lithium-ion batteries can also be viewed from a broader perspective, for instance, the use of batteries for the storage of electrical energy generated by renewables such as solar or wind power thereby allowing the grid to be stabilized against variable demand for power. Such applications will require different energy and power densities and corresponding new chemical approaches, such as a cathode of a single host where a singly charged cation is inserted reversibly and over a finite solid–solution range (Goodenough and Park, 2013).

As noted above, historically lithium-ion batteries have been disposed along with general waste in landfill as it has not been economically viable to recycle. Recently, technological developments have the potential to support recycling batteries in the future. In 2005, 1100 t of heavy metals and more than 200 t of toxic electrolytes were recovered from 4000 t of used lithium-ion batteries (Ordoñez et al., 2016). The demand for lithium ion batteries increases with the wider adoption of electric vehicles, so the potential for the contamination of soil increases without an associated recycling ability. There are certain challenges associated with recycling lithium-ion batteries and these are principally the disposal of harmful waste as well as avoidance of explosion during waste processing caused by radical oxidation of the lithium metal produced from battery materials (Xu et al., 2008). Disposal itself needs to include processing of a variety of different metallic and chemical compounds as depicted in Fig. 4. The diverse components of lithium ion batteries as shown in Fig. 4, complicates the processes for recycling and acts as an inhibiting factor in encouraging the safe disposal of electric vehicle components.

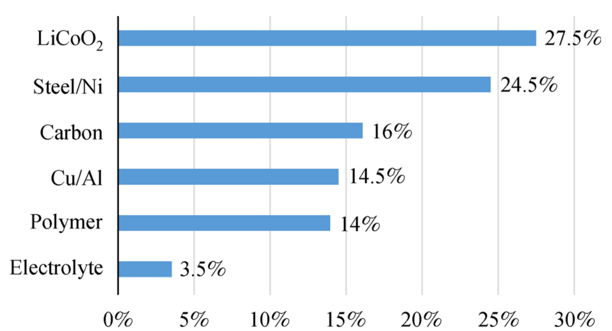

Fig. 4 Chemical composition of a typical lithium-ion secondary rechargeable battery (source of data: Xu et al., 2008).

Any successful improvements in technology will be required to be followed by an acceptance by the consumer to drive a wide adoption of electric vehicles. As with all activity driven by a consuming public, there is no certainty on how individuals will respond to a given change in a product. The following section outlines some of the considerations on the acceptance and use of electric vehicles.

5 Consumer influence on economic and environmental factors

The world of management is complex due to the uncertainty of human responses to change. The unintended consequences of decisions can result in outcomes greatly different than anticipated. Although electric vehicles have been proposed for about as long as steam, gasoline and diesel vehicles, the predominant choice until very recently has been the gasoline vehicle for personal use. Comparing real world economic and environmental factors for gasoline versus electric vehicles is greatly impacted by the changes in the owner's purchasing decisions and driving behavior.

Leard et al. (2017) show that a consumer trend for 2% heavier vehicles per year, which started around the year 1976, has since leveled off in 2004. That is, although the combustion engine powering vehicles have improved greatly since 1972, the actual economic benefit has not been realized because the vehicles themselves have increased in weight. Greater advances in fuel efficiency for gasoline engines since 2004 has been offset however by the unabated demand for horsepower with an increase of about 4% more power per year for the average vehicle sold in the United States (US). Electric vehicles can provide better acceleration and therefore power consumption than gasoline or diesel vehicles. Therefore, choosing a more efficient engine or one with lower environmental impact under constant conditions may not result in any benefit if the driver chooses to adjust behaviors to counter the benefits. Therefore, in the following section we will restrict the comparison to the choice of assuming the consumer would view the two vehicle types with the same criteria. That is, we compare the economic and environmental characteristics of gasoline and electric vehicles assuming the consumer would view them as equivalent transportation tools (equivalent size and power), ignoring that consumer choice is not always rational as outlined above and may be impacted further by subjective influences. It is assumed that a common situation for consumers is whether to keep their existing gasoline powered vehicle or exchange it for one that is electric powered. We performed an analysis of the environmental impact and economics of such a case.

There are many factors that can greatly impact the realized fuel economy of a gasoline powered vehicle. In areas where winters are typically below freezing, fuel economy is particularly worse during the time required to fully warm the fluid in an automatic shift four-wheel or all-wheel drive vehicle (Jehlik et al., 2015), making them poorly suited for short haul urban trips. Also, frequent stopping and acceleration decrease the achievable fuel economy. The optimum fuel economy for gasoline vehicles is at a steady speed down a straight highway. Electric vehicles, however, tend to be more efficient when driven in a typical urban environment with short trips. This is due to the ability to partially regenerate the kinetic energy back to electric energy during braking (Wu et al., 2015). Thomas et al. (2017) report that the energy consumption of electric vehicles is impacted more by driving style than gasoline vehicles. Electric vehicles benefit most by a less aggressive driving style (lower rates of acceleration and deceleration), due to a greater efficiency at regeneration with smoother operation. With the above factors noted, the analysis for this paper uses average US Environmental Protection Agency (EPA) energy consumption rates, recognizing that the values are useful for comparison purposes (particularly between gasoline vehicles) but may not accurately reflect realized absolute energy consumption levels in practical use (Greene et al., 2017).

Representative 2018 vehicles from among traditionally higher selling models were selected for comparison (Davis et al., 2017). The summary data of the vehicle base manufacturer's suggested retail price in California (USA), fuel consumption and weight are presented in Table 1. Larger pickup trucks were not included in the data collection as they are not tested using the same EPA standards as cars and light trucks, and there is not a consistent manner to measure their fuel economy (Lutsey and Sperling, 2005).

Figure 5 shows the manufacturer's suggested retail price as listed on their websites for the vehicles considered versus the weight of the vehicle. As noted in Table 1, the weight of the battery packs for the electric and hybrid cars

Table 1 Data on representative vehicles as sourced from vendors' websites (2018)

Vehicle (2018 model)	Energy source	Weight (kg)	EPA rated fuel consumption (mpg)	Manufacturer's suggested retail price (USD)
Chev Bolt	Electric	1420*	110	37,495
Nissan Leaf	Electric	1266*	100	30,000
Ford Focus	Electric	1354*	107	29,120
Hyundai Ioniq	Electric	1120*	136	29,500
Kia Soul	Electric	1176*	108	33,950
VW eGolf	Electric	1286*	118	30,500
Tesla Model 3	Electric	1354*	123	35,690
Toyota Prius	Hybrid	1070*	46	20,630
Honda Accord	Hybrid	1470*	47	25,100
Ford Fusion	Hybrid	1587*	42	25,390
Toyota Highlander	Hybrid	1954*	29	36,670
Chev Malibu	Hybrid	1403*	44	28,800
Chrysler Pacifica	Hybrid	1964*	32	40,000
Cadillac CT6	Hybrid	1880*	25	75,100
Toyota Tundra	Gasoline	2400	17	48,300
Cadillac Escalade	Gasoline	2535	17	74,000
Toyota Yaris	Gasoline	1081	42	17,460
Nissan Altima	Gasoline	1457	26	24,125
Dodge Journey	Gasoline	1732	19	24,140
Ford Fiesta	Gasoline	1171	30	14,200
Honda Civic	Gasoline	1250	36	18,840
Chrysler Pacifica	Gasoline	1964	23	27,000
Toyota Highlander	Gasoline	1879	24	31,000
KIA Nitro	Gasoline	1409	50	23,340
BMW X5	Gasoline	2190	24	59,500
Ram 2500	Gasoline	2866	21	32,545
Chevy Cruze	Diesel	1464	35	26,800
Chevy Equinox	Diesel	1636	32	31,700
Jaguar XE	Diesel	1510	36	37,225
BMW X5	Diesel	2215	29	43,100
Ram 2500	Diesel	3030	23	61,000

* Denotes vehicle weight not including batteries; mpg, EPA miles per gallon equivalent energy consumption as reported by vendor.

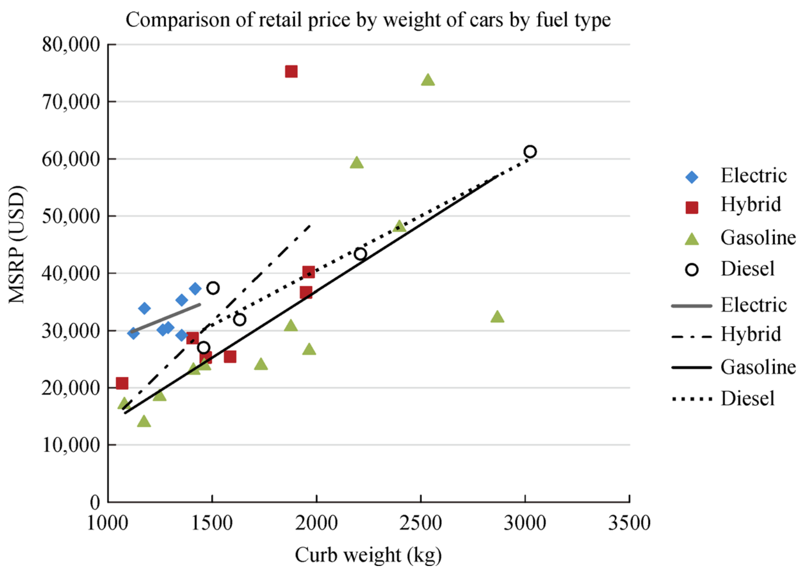

Fig. 5 Retail cost of vehicle by fuel type.

have been subtracted from the analysis. This was done to reflect the cost of the vehicle according to the relative useable space. That is, a consumer would prefer having no battery weight in the vehicle, but may prefer additional cargo space and hence the perceived size of the vehicle from the consumer's view would not include the dense mass of the batteries. The weight of a battery pack is around 300 kg for battery powered electric vehicles and around 80 kg for hybrids. The electric vehicles are all lighter than the lightest diesel vehicle. It has been widely reported (e.g., Levinson, 2016) that in order to meet average fuel economy standards manufacturers discount smaller gasoline vehicles and place a much higher margin on their larger, more popular, vehicles. This may be one factor responsible for the greater spread of the cost by weight for the heavier vehicles as seen in Fig. 5. The gasoline vehicles are available in a wider range of sizes and, in general, are lower capital cost than any of the other fuel type alternatives.

As demonstrated in Fig. 5, the cost of a vehicle is generally correlated to its weight, with diesel and gasoline vehicles being similar on a cost per kilogram basis, especially at the heavier end. As noted, diesel vehicles tend to be heavier and consumers tend to choose larger vehicles when they select the diesel alternative. The premise of better efficiency and a financial benefit is overcome by upgrading to a larger vehicle. The large variability in the cost per kilogram supports the idea that vehicle purchases are not totally driven on a financial basis, as would be expected. Selecting an electric vehicle comes with a requirement to pay more for the physical amount of vehicle the consumer receives. Decisions on a cost basis do not, therefore, hold up well to simple generalizations and are very dependent upon the specific vehicle (i.e., make, model, and options) being considered.

The fuel economy for the gasoline, hybrid and diesel vehicles are as much impacted by vehicle weight as fuel type as shown in Fig. 6. That is, choosing a smaller gasoline vehicle can improve fuel economy to approximately as much a degree as choosing the same original sized hybrid or diesel vehicle. The electric vehicles are all much more efficient than the other types. This is largely due, however, to the low efficiency of the combustion cycle in the vehicles with conventional engines compared against the much higher efficiency of simply charging batteries. That is, when coal or natural gas is combusted to generate the electricity at a remote site, the inefficiency of that energy conversion is not included in the mgpe measured for electric vehicles (Noori et al., 2015). Indeed, from a lifecycle analysis of the environmental impact perspective, the electric vehicle fuel consumption including the generation of the electricity may be more similar to gasoline vehicles depending on the source of energy used.

In terms of the environmental impact of producing a vehicle, Ellingsen et al. (2016) provide data suggesting that the energy required to manufacture a vehicle is equivalent to driving about 30,000 miles and the energy to create a battery for an electric vehicle is equivalent to driving an additional 15,000 miles. Therefore, scrapping a functional gasoline vehicle for an electric one will create an immediate increased environmental impact with a potential benefit only realized a number of years into the future. Again, the environmental impact of the electric vehicle appears much lower in Fig. 6, but again we note that the energy required to produce the electricity at a remote location is not included in these figures. The environmental impact of charging a car using nuclear, wind or hydro produced electricity will be much different than if the

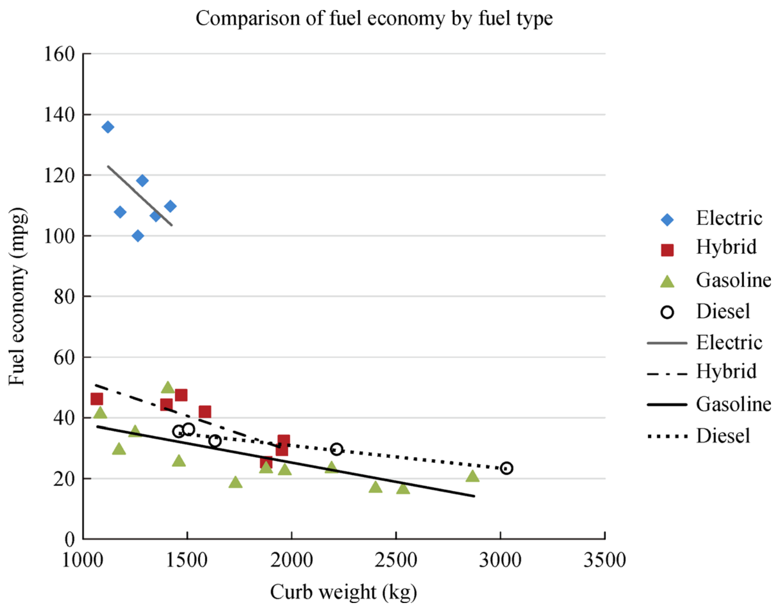

Fig. 6 Fuel economy by weight and fuel type.

source is coal, natural gas or diesel.

To make a decision on economics, one, of course, cannot only consider the purchase price. To evaluate the overall cost of the various vehicle types, a lifecycle analysis is required. This is provided in the next section.

6 Lifecycle cost comparisons

As noted earlier, consumer decisions are not always rational from an economic perspective, even when the consumer may believe they are doing it. The environmental impact of vehicles is not simply determined by the amount of tailpipe emissions per kilometre driven. As also noted, human factors influence total effects, such as increased driving when the perception of lower impact is believed. Similarly, the overall cost of driving a vehicle is not only determined by the initial purchase price and the normalized fuel economy per kilometre. This section looks further into the lifecycle cost of the various vehicle types being considered.

To compare the cost of driving different vehicle types, the costs were broken into an annualized capital cost, fuel cost and special maintenance costs. For comparison purposes, it was assumed that the maintenance costs, such as tire wear, repairs and preventative work would be comparable for all vehicles and were not included. For electric vehicles, however, it has been noted (e.g., Neubauer et al., 2015) that the batteries have a shorter life than the vehicle in general, and an expected cost of around 1100 USD per year should be associated with their replacement. Because of a much smaller electric capacity, battery pack replacement in hybrids would be around 200 USD per year. A personal vehicle is driven about 11,000 miles on average in the US (Cirillo et al., 2017). It must be again noted that people change their habits depending on vehicle choices which makes direct comparisons difficult. Neumann et al. (2015) found that drivers of electric vehicles change their driving behavior over time as they become more aware of strategies to increase efficiency and extend the distances that can be attained on a single charge. The time needed to charge and the lower availability compared to gasoline vending stations creates a motivation for the electric vehicle driver to conserve energy more than a gasoline vehicle driver.

To provide a common ground for performing the analysis, certain assumptions were made to compare the different vehicle types. The following assumptions were selected for our comparison:

• 10% of the purchase price was taken as the annualized capital cost of the vehicle.

• Since the capital cost and fuel economy trend according to vehicle weight, a normalized value was used assuming a vehicle weight of 1300 kg, which represents the average for the electric vehicles selected.

• Electricity cost of 13 cents/kWh (Burke and Abayasekara, 2018).

• Gasoline 2.70 USD per gallon.

• Diesel 2.90 USD per gallon (Goncharuk et al., 2018).

The annual normalized driving cost for each vehicle type is shown in Fig. 7.

The perception that electric vehicles provide the consumer with a lower cost alternative to conventional gasoline fueled cars is not supported by Fig. 7. As noted throughout this paper, consumer choice is often driven by preferences not in line with a purely economic rationale. Factors such as style, performance, and marketing motivate people to buy certain models, which do not

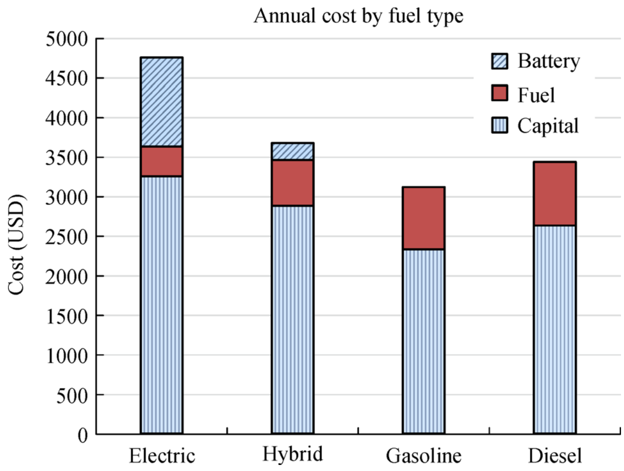

Fig. 7 Annual cost normalized for 1300 kg vehicle.

support any economic basis for the purchase. The consumer preference for less fuel efficient gasoline vehicles motivates the vendors to increase the margin on the popular larger vehicles to subsidize smaller vehicles to reach an acceptable market price in order to meet mandated efficiency targets. Figure 7 demonstrates that choosing a small gasoline vehicle is the best economic choice in the current pricing environment. Regional variations in taxes, electricity prices, and fuel prices can potentially change the results as presented. However, it would be unlikely that differences would be substantial to change the general conclusion supported here that vehicle size has a greater impact on overall cost of driving than the source of energy.

Given that the total cost of ownership is dependent upon many local variables specific to each situation, providing equations to reflect average situations may be misleading. Government taxes or incentives, local power costs, local fuel costs, manufacturer's incentives or general pricing policies, and variations of all of these factors over time would make simple general formulas more misleading than informative. These comparisons are also dependent upon future adoption trends and degree of infrastructure development, which are examined in the next section.

7 Trends, challenges, and outlooks

A key determinant impacting the adoption of electric vehicles is the availability of charger points, both in terms of the number of chargers as well as the relative geographic distribution especially in more populated areas. The use of chargers presents its own challenge in terms of the impact on the power distribution grid regarding power losses and voltage deviations, where uncoordinated power consumption can potentially lead to certain grid problems (Clement-Nyns et al., 2010). The actual chargers are classified as slow chargers and fast chargers with different charge schemes. Related factors to be considered include infrastructure requirements and grid impacts, the role of connectors, charger/vehicle communications, time-of-use electricity costs, and grid upgrades/synergies (Botsford and Szczepanek, 2009). Additionally, there are various materials considerations to be addressed, including developing the next generation electrodes (anode and cathode) and electrolyte materials for these energy storage applications (Manthiram, 2011).

Regarding availability of electrical charger stock for electrical vehicles worldwide, we can see that the number of slow and fast chargers has grown dramatically from 3682 and 373 in 2010 to 212,394 and 109,871 in 2016 respectively (International Energy Agency, 2018). This growth is depicted in Fig. 8. Application of polynomial regression analysis (order = 2) to this data further highlights that the number of slow chargers and fast chargers is expected to reach 600,000 units ($R^2 = 0.9936$) and 400,000 units (R^2 = 0.8845) in 2020, respectively. The R^2

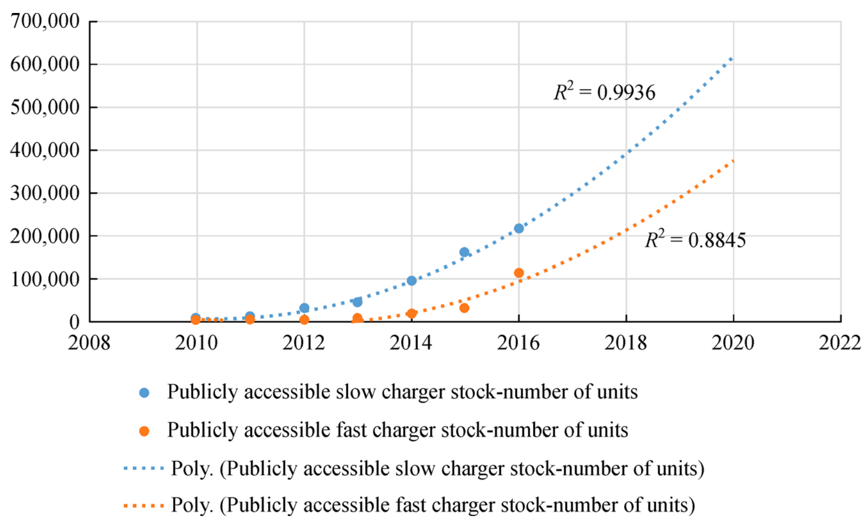

Fig. 8 Worldwide growth in publicly accessible chargers (slow and fast), source of data: International Energy Agency (2018).

(coefficient of determination) values indicate that there is greater confidence in the projected data for slow chargers than fast chargers. Although these are estimated figures based on trend-line analysis, it can clearly be observed that the number of chargers is expected to significantly increase over the next few years; this greater availability of chargers will further underpin the expected growth in electric vehicles.

On the matter of the registration growth in both battery electric vehicles and plug-in hybrid electric vehicles, we can consider the level of worldwide new car registrations (International Energy Agency, 2018). Figure 9 highlights the number of electric car new registrations, showing the number for battery vehicles has risen dramatically from 2010 to 2016.

Application of polynomial regression analysis (order = 2) to this data further highlights that the number of registrations is expected to reach 1.3 million ($R^2 = 0.9963$) for battery, 0.7 million ($R^2 = 0.9933$) for plug-in hybrid and 2 million ($R^2 = 0.9972$) total in 2020. These projections are estimates although the R^2 (coefficient of determination) values indicate a good level of confidence in the projected data. This analysis would appear to indicate that the number of new battery electric vehicle registrations will continue to outstrip new plug-in hybrid vehicle registrations.

8 Discussion and summary remarks

Environmental issues and the spectre of diminishing fossil fuel reserves have sparked interest in challenging the traditional methods of transportation. A personal vehicle fuelled by relatively inexpensive gasoline may not be the optimal means to move people. This paper has attempted to provide an analysis of the increasing popularity of electric vehicles in consumer choice and public policies.

• While electric vehicles are nothing new, they are gaining traction although the increased popularity is not always driven by rational analysis.

As described in the introduction, electric vehicles have been technically possible for about as long as gasoline vehicles have been around. Only in recent decades has there been solid consumer interest. A common modern perception is that electric vehicles are cheaper to operate and better for the environment but this is not conclusively supported by the findings above.

• ATEA was chosen to investigate electric vehicle adoption.

• Tailpipe emissions do not measure full environmental impacts.

Section 3 outlined the complicating factors on the environmental effects of the various types of vehicles available. Human factors that cannot be reliably predicted for any given situation can produce impacts not intended by the user. When intentions appear to drive consumer choices, the result can be opposite to those intentions.

• Technological advances create complexity.

The increased use of batteries for powering transportation can impact infrastructure requirements and change the cost of commodities in a difficult to predict direction. Supply of raw materials may also create changes in general market pricing which influences the accuracy of present decisions.

• A potential unintended consequence of widespread electric vehicle use could be land contamination if recycling of batteries is not economically sustainable.

Section 4 outlined that there is good potential for technological improvements to significantly change the general results of the analysis for a situation in the near

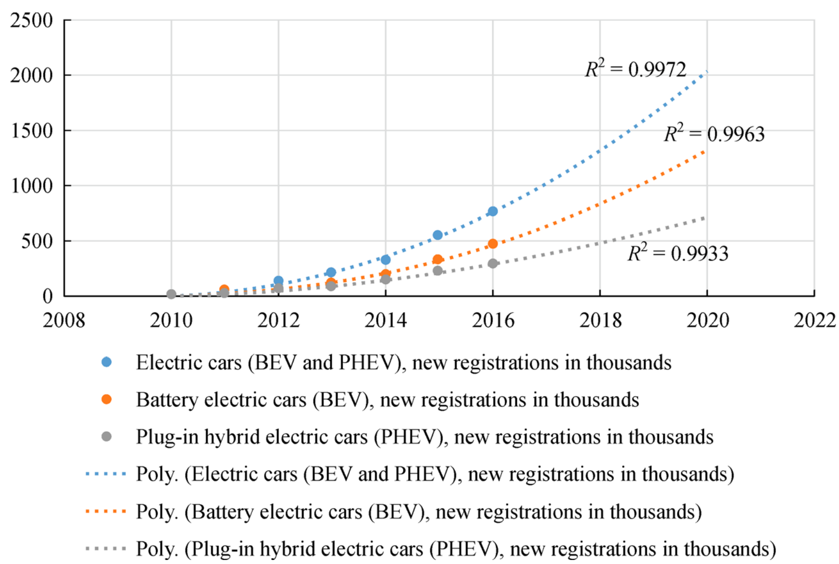

Fig. 9 Worldwide growth in electric car new registrations in thousands (source of data: International Energy Agency, 2018).

future, considering predictions two decades ago that no viable replacement would exist now for lead batteries. Past advances do not guarantee that significant improvements can be made, considering the restraints of chemical and physical reality. The behavior of humans further complicates intentions by the trend for increased driving of new or more efficient vehicles that negates the reductions per distance traveled. If consumers are purchasing battery powered electric vehicles specifically for their short trips, it may be more beneficial to educate and encourage the use of public transportation, walking or biking. The operational savings and decreased emissions resulting from simply choosing a smaller vehicle for personal use and reducing driving distances will be similar to switching to battery powered electric vehicles.

- A straight forward general guiding principle is not likely to be supported by reality.
- The data suggests a small gasoline vehicle is presently the best economic choice although this may change at some point in the future.

Sections 5 and 6 showed that the range of vehicles presently available, including their purchase price, complicate the factors that could lead to definitive guiding principles. But based on the present data as collected, it appears that keeping a fully functional gasoline vehicle has a better immediate environmental impact than the emissions required for manufacture and distribution of a more efficient battery powered electric vehicle.

- Trends and changes may require new analyses.

Section 7 highlights how increased use of electric cars will place higher demands on domestic electricity distribution systems where increased levels of electric vehicle use could result in a situation where such distribution capacities are exceeded. This points to the need for systemic level modeling of overall electric and power networks as well as potential unintended consequences of adopting perceived cleaner road transport vehicles.

This study did not investigate the benefits of autonomous (driverless) vehicles, which are closely associated with battery powered electric vehicle technology. If improved safety is clearly demonstrated by machine controlled electric powered vehicles, it is foreseeable that the future of hydrocarbon powered vehicles may be phased out sooner than most people would believe. But this study suggests that we are not at that point yet.

9 R&D agenda for the adoption of electric vehicles

This research study has enabled synthesis of a set of proposed research and development (R&D) areas (Table 2) which should be investigated to adequately address the issues highlighted in this TEA on the adoption of electric vehicles.

Table 2 Proposed research and development areas for the adoption of electric vehicles

Area of consideration	Proposed research and development areas
Environmental considerations	• Life-cycle analysis (LCA) for electric vehicles, which examines the impact of electrical generation via alternative means, such as from burning of different types of fossil fuels (namely coal and natural gas), bio-organic waste as well as from renewable sources • Cost-benefit analysis on vehicle scrappage schemes and the impact on consumer behaviors and electric vehicle sales • Improved techniques for recycling different materials from lithium-ion based batteries utilized in electric vehicles to improve the sustainable production of battery materials
Technological advances	• Further development of technologies to enable a reduction of the costs associated with large-scale production of lithium-ion batteries • Further development of technologies to reduce the weight of batteries (for both lithium-ion and other types) for electric vehicles • Understanding lithium-ion battery technology maturity using the S curve model in order to identify the current level of maturity and future trajectories for the technology • Understanding the technological and economic risks arising from large scale lithium-ion battery production across the automotive sector and the resultant impact on levels of the commercial sources of lithium
Consumer influence on economic and environmental factors	• Further benchmarking analysis of automobiles to understand the impact of different driving situations (i.e., different driving styles and weather conditions) on realized fuel efficiencies
Lifecycle cost comparisons	• Economic analysis on lifecycle costs for electric vehicles to take account of the impact of certain contributing factors, such as regional variations in taxes, electricity prices, and fuel prices. Discounted cash-flow techniques to be employed where possible
Electric vehicle infrastructure-battery chargers	• Development of improved battery charger technologies that enable faster charging times • Economic modeling to examine alternative business models to support large scale roll-outs of electrical vehicle charging infrastructure. Economic analysis to examine potential options for joint public/private sector investment strategies to be deployed to address the significant capital needs of such initiatives
Registrations of electric vehicles	• International benchmarking studies on the adoption rates for electric vehicles to examine the impact of local factors as well as cultural influences on the transition rates to electric vehicles in different countries and regions

References

Ajanovic A, Haas R, Wirl F (2016). Reducing CO_2 emissions of cars in the EU: analyzing the underlying mechanisms of standards, registration taxes and fuel taxes. Energy Efficiency, 9(4): 925–937

An S J, Li J, Daniel C, Mohanty D, Nagpure S, Wood D L III (2016). The state of understanding of the lithium-ion-battery graphite solid electrolyte interphase (SEI) and its relationship to formation cycling. Carbon, 105: 52–76

Avci B, Girotra K, Netessine S (2014). Electric vehicles with a battery switching station: adoption and environmental impact. Management Science, 61(4): 772–794

Bastian A, Börjesson M, Eliasson J (2016). Explaining “peak car” with economic variables. Transportation Research Part A: Policy and Practice, 88: 236–250

Bernasek A (2002). Ten things to keep you up at night. Fortune, 145(9): 61–62

Botsford C, Szczepanek A (2009). Fast charging vs. slow charging: pros and cons for the new age of electric vehicles. In: Proceedings of 24th International Battery Hybrid Fuel Cell Electric Vehicle Symposium, Stavanger, Norway

Burke P J, Abayasekara A (2018). The price elasticity of electricity demand in the United States: a three-dimensional analysis. Energy Journal, 39(2): 123–145

Catenacci M, Verdolini E, Bosetti V, Fiorese G (2013). Going electric: expert survey on the future of battery technologies for electric vehicles. Energy Policy, 61: 403–413

Cirillo C, Liu Y, Tremblay J M (2017). Simulation, numerical approximation and closed forms for joint discrete continuous models with an application to household vehicle ownership and use. Transportation, 44(5): 1105–1125

Clement-Nyns K, Haesen E, Driesen J (2010). The impact of charging plug-in hybrid electric vehicles on a residential distribution grid. IEEE Transactions on Power Systems, 25(1): 371–380

Dadush S (2018). Why you should be unsettled by the biggest automotive settlement in history? University of Colorado Law Review Forum, 89

Davis S C, Williams S E, Boundy R G, Moore S A (2017). 2016 Vehicle Technologies Market Report (No. ORNL/TM-2017/238). Oak Ridge National Laboratory, Oak Ridge, TN

Dewulf J, Van der Vorst G, Denturck K, Van Langenhove H, Ghyoot W, Tytgat J, Vandeputte K (2010). Recycling rechargeable lithium ion batteries: critical analysis of natural resource savings. Resources, Conservation and Recycling, 54(4): 229–234

Egbue O, Long S (2012). Critical issues in the supply chain of lithium for electric vehicle batteries. Engineering Management Journal, 24(3): 52–62

Ellingsen L A W, Singh B, Strømman A H (2016). The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. Environmental Research Letters, 11(5): 054010

Gaines L (2014). The future of automotive lithium-ion battery recycling: charting a sustainable course. Sustainable Materials and Technologies, 1: 2–7

Gerarden T D, Newell R G, Stavins R N (2017). Assessing the energy-efficiency gap. Journal of Economic Literature, 55(4): 1486–1525

Gerssen-Gondelach S J, Faaij A P (2012). Performance of batteries for electric vehicles on short and longer term. Journal of Power Sources, 212: 111–129

Goncharuk A G, Havrysh V I, Nitsenko V S (2018). National features for alternative motor fuels market. International Journal of Energy Technology and Policy, 14(2–3): 226–249

Goodenough J B, Park K S (2013). The Li-ion rechargeable battery: a perspective. Journal of the American Chemical Society, 135(4): 1167–1176

Graham-Rowe E, Gardner B, Abraham C, Skippon S, Dittmar H, Hutchins R, Stannard J (2012). Mainstream consumers driving plug-in battery-electric and plug-in hybrid electric cars: a qualitative analysis of responses and evaluations. Transportation Research Part A: Policy and Practice, 46(1): 140–153

Greene D L, Khattak A J, Liu J, Wang X, Hopson J L, Goeltz R (2017). What is the evidence concerning the gap between on-road and Environmental Protection Agency fuel economy ratings? Transport Policy, 53: 146–160

Grosjean C, Miranda P H, Perrin M, Poggi P (2012). Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry. Renewable & Sustainable Energy Reviews, 16(3): 1735–1744

Hofmann J, Guan D, Chalvatzis K, Huo H (2016). Assessment of electrical vehicles as a successful driver for reducing CO_2 emissions in China. Applied Energy, 184: 995–1003

International Energy Agency (2018). Global EV Outlook 2017—two million and counting. International Energy Agency

Jehlik F, Wood E, Gonder J, Lopp S (2015). Simulated real-world energy impacts of a thermally sensitive powertrain considering viscous losses and enrichment. SAE International Journal of Materials and Manufacturing, 8(2): 239–250

Kley F, Lerch C, Dallinger D (2011). New business models for electric cars—a holistic approach. Energy Policy, 39(6): 3392–3403

Klöckner C A, Nayum A, Mehmetoglu M (2013). Positive and negative spillover effects from electric car purchase to car use. Transportation Research Part D: Transport and Environment, 21: 32–38

Larson P D, Viáfara J, Parsons R V, Elias A (2014). Consumer attitudes about electric cars: pricing analysis and policy implications. Transportation Research Part A: Policy and Practice, 69: 299–314

Leard B, Linn J, McConnell V (2017). Fuel prices, new vehicle fuel economy, and implications for attribute-based standards. Journal of the Association of Environmental and Resource Economists, 4(3): 659–700

Levinson A (2016). Energy efficiency standards are more regressive than energy taxes: theory and evidence. National Bureau of Economic Research Working Paper 22956, National Bureau of Economic Research, Inc.

Lucsko D N (2014). Of clunkers and Camaros: accelerated vehicle retirement programs and the automobile enthusiast, 1990–2009. Technology and Culture, 55(2): 390–428

Lutsey N, Sperling D (2005). Energy efficiency, fuel economy, and policy implications. Transportation Research Record: Journal of the Transportation Research Board, 1941(1): 8–17

Manthiram A (2011). Materials challenges and opportunities of lithium ion batteries. Journal of Physical Chemistry Letters, 2(3): 176–184

Neubauer J S, Wood E, Pesaran A (2015). A second life for electric vehicle batteries: answering questions on battery degradation and value. SAE International Journal of Materials and Manufacturing, 8 (2): 544–553

Neumann I, Franke T, Cocron P, Bühler F, Krems J F (2015). Eco-driving strategies in battery electric vehicle use—how do drivers adapt over time? IET Intelligent Transport Systems, 9(7): 746–753

Noori M, Gardner S, Tatari O (2015). Electric vehicle cost, emissions, and water footprint in the United States: development of a regional optimization model. Energy, 89: 610–625

Nykvist B, Nilsson M (2015). Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change, 5(4): 329–332

Ordoñez J, Gago E J, Girard A (2016). Processes and technologies for the recycling and recovery of spent lithium-ion batteries. Renewable & Sustainable Energy Reviews, 60: 195–205

Scrosati B, Garche J (2010). Lithium batteries: status, prospects and future. Journal of Power Sources, 195(9): 2419–2430

Shiller R J (2007). Understanding recent trends in house prices and home ownership (No. w13553). National Bureau of Economic Research

Socolow R, Thomas V (1997). The industrial ecology of lead and electric vehicles. Journal of Industrial Ecology, 1(1): 13–36

Swanson R M, Platon A, Satrio J A, Brown R C (2010). Techno-economic analysis of biomass-to-liquids production based on gasification. Fuel, 89: S11–S19

Thomas J, Huff S, West B, Chambon P (2017). Fuel consumption sensitivity of conventional and hybrid electric light-duty gasoline vehicles to driving style. SAE International Journal of Fuels and Lubricants, 10(3): 2017-01-9379

Van Haaren R (2011). Assessment of electric cars’ range requirements and usage patterns based on driving behavior recorded in the National Household Travel Survey of 2009. Earth and Environmental Engineering Department, Columbia University, Fu Foundation School of Engineering and Applied Science, New York, USA

Van Vliet O, Brouwer A S, Kuramochi T, Van Den Broek M, Faaij A (2011). Energy use, cost and CO_2 emissions of electric cars. Journal of Power Sources, 196(4): 2298–2310

Van Wee B, Moll H C, Dirks J (2000). Environmental impact of scrapping old cars. Transportation Research Part D: Transport and Environment, 5(2): 137–143

Weiss M, Patel M K, Junginger M, Perujo A, Bonnel P, van Grootveld G (2012). On the electrification of road transport-Learning rates and price forecasts for hybrid-electric and battery-electric vehicles. Energy Policy, 48: 374–393

Wu X, Freese D, Cabrera A, Kitch W A (2015). Electric vehicles’ energy consumption measurement and estimation. Transportation Research Part D: Transport and Environment, 34: 52–67

Xu J, Thomas H R, Francis R W, Lum K R, Wang J, Liang B (2008). A review of processes and technologies for the recycling of lithium-ion secondary batteries. Journal of Power Sources, 177(2): 512–527

Yang H X, Zhou W, Lou C Z (2009). Optimal design and techno-economic analysis of a hybrid solar-wind power generation system. Applied Energy, 86(2): 163–169

Yao Y, McDowell M T, Ryu I, Wu H, Liu N, Hu L, Nix W D, Cui Y (2011). Interconnected silicon hollow nanospheres for lithium-ion battery anodes with long cycle life. Nano Letters, 11(7): 2949–2954

Zoulias E I, Lymberopoulos N (2007). Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems. Renewable Energy, 32(4): 680–696