The analysis for the development of transportation electrification

Yixin Liu[1, †], Zechen Li[2, *, †], Fanzelin Wan[3, †]

[1] Department of Mechanical, Material and Manufacturing Engineering, University of Nottingham Ningbo China, Ningbo, 315100, China

[2] College of Electrical Engineering, Zhejiang University, Hangzhou, 310013, China

[3] Department of Chemistry, University of Edinburgh, Edinburgh EH9 3JW, United Kingdom

* Corresponding Author Email: 3170105855@zju.edu.cn

[†]These authors contributed equally.

Abstract. For the last hundreds of years, fossil fuel and internal combustion engine has promoted the quality of people's lives greatly. However, fossil fuel also causes many problems. Oil is being running out and burning fossil fuel emits too much greenhouse gases. So, finding other energy sources to get rid of fossil fuel is important. Electricity is a kind of clean energy and transportation is one of the main consumers of fossil fuel. Therefore, transportation electrification will be a great method to deal with the trouble caused by burning fossil fuel. This paper summarizes the advantages and limitations of transportation electrification by analysing the electrical machinery and drawbacks of batteries concisely. Electric vehicles (EVs) have many benefits: electric machinery with good properties makes EVs more powerful and faster; using electricity could not only reduce emission of greenhouse gases, but also save customers' money. But the batteries have more safety issues than internal combustion engine, like easily catching fire or exploding after being crushed. Batteries also have bad performance in extreme situation, which affects the range of EVs. And lack of charging stations reinforces the 'range anxiety'. This paper puts forward some ideas to improve the EVs and expects that EVs have great potential to replace the internal combustion engine cars (ICE cars) in the future.

Keywords: Transportation electrification, Internal combustion engine, Greenhouse gas, Electrical machinery.

1. Introduction

Fossil fuel has supported human beings for hundreds of years. However, since the past one hundred years, petrol consumption has increased rapidly and oil will be run out within a few generations. Meanwhile, global warming has become a severe problem due to high carbon dioxide emissions from any source that burns fossil fuel. The global temperature is rising every year, resulting in the melting of icebergs in glacial areas. This gives the rise of the sea level, which causes the reduction of the habitat of endangered animals such as penguins and polar bears. So, it is urgent to explore new energy source to replace fossil fuel. Water energy, wind energy, solar power, nuclear energy is all abundant with no pollution. But before such energy could be used, it has to be transformed into electricity. As a result, electrification has become an inevitable trend, and transportation electrification is an important part in this trend. After the invention of lithium-ion batteries, the range of EVs has been longer and longer and EVs have been familiar to the public gradually. Nowadays, there are many EV brands, such as Tesla, Lexus, BYD. As for trains electrification, almost all the underground in the world is powered by electrical machinery. In China, high-speed trains have nearly connected all the cities. However, the development of transportation electrification is still not mature enough, there are many insufficient aspects that people need to overcome, such as the storage of electricity, the transformation from sustainable energy to electricity, and increasing the travelling range for EVs. So, it is necessary to explore why trains electrification has become a success while EVs still face a lot of trouble.

Currently, research about EVs' benefits or drawbacks has some main interests. One interest is to compare the cost of EVs with ICE cars, which indicates that the cost of EVs is lower generally. Another interest explores the method to control the noise of EVs. Some research analyses the impact of charging an EV on the electric system. Besides, more research is about the battery limitation, which affects the performance of EVs dramatically. But the overview of transportation electrification is not sufficient.

The main goal of this paper is to summarize the specific advantages and limitations of transportation electrification. The research presents the electricity applications to transportation. Then it analyses the property, environmental and economic advantages with four issues, range, safety, recycling and the challenge to distribution network. Finally, it puts forward some ideas to improve the situation of EVs.

2. Transportation electrification

2.1. The development of EVs

In the last decade, the process of electrification of cars has been considered a great success. In 2020, 10 million EVs were sold worldwide, with an increment of 43% compared to 2019. With 4.5 million, China has the largest number of EVs, although Europe had the maximum yearly growth to reach 3.2 million in 2020 [1]. As the EV market has increased rapidly, there are several problems that people need to face. Take China in 2021 as an example, there were 7.8 million EVs, and the total electricity produced in China was 8 million GWh. As an EV's estimated average battery capacity was 90 kWh, the total amount of electricity produced in 2021 could support 244 million cars to charge daily for a year. Comparing the two numbers above, 244 million is much higher than 7.8 million. However, not all the electricity was used for charging, there were many other usages. As the number of EVs is increasing at a very high speed, the pressure on the power supply would be much harder. If the electricity needed for the charging of EVs is not sufficient, the power plant would be overloaded and there would not have enough energy to transform into electricity. According to the previous statement, the development of private cars was quite fast as the government has promulgated policies that benefit the EV owners, and the electric utilities, governments, and private entities continue building a robust network of charging stations. Most families in the United States and other European countries tend to buy Tesla Model-3, as this was the best-selling car worldwide [2-4]. In China, although the number of EVs was increasing, the percentage of EVs was relatively low compared to other countries.

2.2. The electrification of the railway system

In recent years, China has achieved a milestone on the electrified railway. The percentage of electrification of the Chinese railway is almost 70% and China has built an electrified railway for 48 thousand kilometers. The advanced development of the Chinese railway benefited from a newly built system called the Permanent Magnet Synchronous Motor (PMSM) traction system based on semiconducting materials. This motor is comprised of a three-phase permanent magnet, a rotor (consisting of permanent magnets), and a stator (consisting of a core with windings and an external frame), with a sinusoidal flux generated, the electromotive force is also sinusoidal. The general principle for this motor is the mutual interaction between the revolving magnetic field of the stator and the constant magnetic field of the rotor. When the rotor's magnetic field is interacting with the alternating current of the stator windings, a torque was created, and the rotor was forced to rotate. Moreover, the PMSM could not start itself due to the rotor poles interlock with the rotating magnetic field of the stator. This phenomenon is caused by the synchronous speed of the rotation of the rotor with the stator field. This system was first used in Shenyang province in 2012 for the underground, and in 2019, its advanced version was designed for high-speed rail vehicles, with a speed of 400 km/h. Furthermore, by the end of 2025, the efficiency of this system would rise by 3%, the cost would be reduced by 10%, and apply to all the undergrounds in the cities in China. The first high-speed train

in China was developed in 2006, with the highest speed of 250 km/h. The latest version of the high-speed train named CR-450 is expected to be put into use in 2025 [5, 6]. The process of electrification of the railway is aimed at fast, safe, and energy conservation, as the induction rotor has a higher efficiency compared to the internal combustion engine.

2.3. The development of waterborne transport

Regarding waterborne transport, a company in Stockholm has developed the most advanced electrified ship in the world. Its technology has reduced energy consumption up to 95% per passenger kilometers in comparison with present vessels, enabling for an unprecedented range of 50 nautical miles at operating speed. In fact, the history of electric drives designed for ships could date back to the 20th century, and nowadays in Europe, around 4,000 ships are driven using electrical means. New technologies for boats only powered by electricity were also developed in China, and these new systems tended to use Li-ion batteries [7, 8].

3. Advantages of transportation electrification

3.1. Property

Nowadays, most EVs are powered by electrical machinery, such as DC motor or PMSM. Electrical machinery has some significant benefits indeed. First, electrical machinery has great starting performance. As for a DC motor, the relationship between the rev (n) and the torque (T) is displayed in Equation (1):

$$n = n_0 - \beta_N T \tag{1}$$

The n_0 in this equation is the no-load torque of the DC motor; the β_N is a constant, which is influenced by armature resistance and if the resistance decreases, β_N will decreases as well. When the motor stops, it has the maximum torque. As the rev rises, the torque drops gradually. However, while the motor is starting, the armature resistance is usually high enough to prevent too much current. And during the start process, the resistance will be reduced moderately to maintain a large enough torque within a large range of speed. As a result, the EV could accelerate to a high speed in a short time. Figure 1 shows such start method.

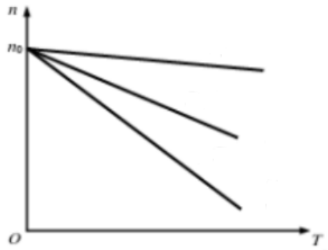

Figure 1. Starting Process with Series Resistance in the Armature Circuit.

On the contrary, internal combustion engine could not produce any torque when it stops. It needs outside force to start it. Therefore, EVs could usually speed up faster. For example, Tesla Model-Y, an EV, could accelerate to 100 kilometers per hour within 5 seconds, while most ICE cars will spend more than 7 seconds. Apart from this, electrical machinery could be controlled easily. The fundamental principle to control the speed of DC motor is to change the armature voltage or exciting current. And based on this principle, there are many methods to control speed, such as fractional-order dynamics, PID and sliding mode control (SMC) [9]. In these ways, the motor speed can be changed smoothly in a wide range. Such properties are suitable for new drivers because they can change the speed of car immediately instead of pushing the pedal too hard.

In addition, linear motor has many great properties and it is widely used in underground. First, linear motor generates power from Ampere force or magnetic force, which depends on the motor

current. If the rated power of motor is high enough, the force generated by motor could be really big. However, as for traditional trains powered by internal combustion engine, traction is no more than their friction of wheels on track. As a result, electric underground could have much bigger traction and better climbing performance. Then, because the force of linear motor is independent of friction, linear motor is the sole power source for maglev trains. In fact, nearly all the high-speed trains have applied electrical machinery [10].

3.2. Environmental

The most significant benefit of EVs is that they do not cause pollution or greenhouse gases when working. It is important to point out that EV do not generate pollution when working indeed, but nowadays, generating electricity which EVs consume still needs to emit CO_2 and such CO_2 is regarded as the emission of EVs. Even so, according to the research from International Energy Agency, the emission of CO_2 of electric cars is about 25% less than the general ICE cars when they run for 400 km [11]. So, transportation electrification is a good way to reduce greenhouse gases.

Currently, main energy source is still fossil fuel. But both oil and coal will run out within a few generations. Electricity is a good power source to replace fossil fuel, which is never exhausted and can be generated from wind, water, solar power or nuclear energy, etc. So, before new material could replace oil as the fuel for internal combustion engine, transportation electrification is a good way to prevent lacking energy source.

EV has a lower noise than ICE car, but EV could create noise with high frequency which is more annoying [12, 13]. Although there are many studies to reduce EV noise, the benefit about low noise of EV is not notable right now.

3.3. Property

EV has lower driving cost. Table 1 shows the cost per 100 km of six different cars.

Table 1. Costs per 100 km of Six Cars.

Type		Price (￥)	Power Consumption (kWh/100km)	Petrol Consumption (L/100km)	Equally Cost (￥/100km)
Electric Vehicles	Tesla Model-Y	394900	13.4	-	25.07
	Lexus UX 300e	385000	13.1	-	23.97
	BYD Tang EV	339800	17.1	-	31.29
Internal Combustion Engine Car	BMW 3-Series	380000	-	6.9	58.65
	Mercedes-Benz C260L	350000	-	6.35	53.98
	Audi A4 Avant	359800	-	6.6	56.1

According to Table 1, it can be demonstrated that the cost of EVs per 100 km is much less than ICE cars. In the past, the price of petrol in China experiences a steady increase. As the price of petrol is rising, the cost gap between EVs and ICE cars will be larger in the future. Research shows that in Latvia, for the cost of the whole lifetime, A new EV would be 27.8% cheaper than a new diesel vehicle and 30% cheaper than a new petrol vehicle. And an EV with 5-year use also is 20% less costly than ICE cars [14]. As for electrical underground, using linear motor could reduce the sectional area of underground because many apparatuses will not be used in the underground anymore, like gearbox. Therefore, the sectional-area of tunnel for underground could be reduced as well, which is about 60% of that of traditional underground tunnel, and it will decrease the construction costs greatly [10].

4. Limitations

Although there are a variety of factors that will facilitate the electrification of transport, the fact remains that there are still many obstacles to this development. The limitations of range, safety and the impact on the network will be discussed in this section.

4.1. Range

At present, many EV manufacturers declare that the range of their products can reach more than 500km which is the identical level to that of ICE cars. However, this is just the data under ideal conditions. In fact, the actual mileage of an EV can be influenced by many factors, especially the extreme cold and hot weather. Research had done by AAA on the range of EVs in cold, moderate and hot weather conditions. The consequences illustrates that there was a considerable reduction in the range of EVs in hot and cold weather. At -6℃, the range was only 41% of that at the optimal temperature (24℃). At 35℃, it was 66% of the normal range [15]. The basic factor for the significant decrease in the EV range at low temperatures is the defect of the lithium batteries. In fact, the optimal operating temperature extent of the lithium-ion batteries in EV is 15℃ to 35℃ [16]. This optimal temperature range is not friendly to northern Europe, Canada and other high latitude regions, because they are lower than it for most of the time in a year. Therefore, the performance of the battery at an inappropriate temperature affects the range and limits the development of transportation electrification.

4.2. Safety

The second limitation of the development of electrified transport is safety issues. The data given by Jinhua at World EV&ES Battery Conference shows that there are more than 3000 EV fire accidents happened in China in 2021. According to the number of nearly 8 million EVs in China, the probability of EV fire is approximate 0.03%, while that of fuel vehicles is about 0.01%-0.02%, which is slightly higher than that of ICE cars [17]. The majority of EV fire incidents are induced by the thermal runaway of lithium-ion batteries. The fundamental reason for the thermal runaway is the high flammability of lithium-ion batteries. Overcharge, short circuits and collision at high speed may lead to the spontaneous combustion of the LIB. In addition, the fire caused by LIB spontaneous combustion is much more dangerous than that caused by fuel vehicles, and it is much more difficult for passengers to escape from EVs than ICE cars during the fire. Firstly, it is due to the LIB fire commonly spreading quickly with the possibility of explosion. Secondly, LIB fire is often accompanied by the production of toxic gases, such as HF, HCN, CO and so on. Intaking these gases may lead to dizziness, exanimation, other uncomfortable symptom and even death [18]. These safety hazards caused by LIB still need to be resolved, thus the safety issues are still an obstacle to electrified transport.

4.3. The Challenge to The Distribution Network

The electrification of transport will lead to a substantial number of EVs being integrated into the National Grid, which may lead to a significant overload of the Distribution Network. Simultaneously, the quality and stability of the whole electric system may be challenged [19, 20]. For instance, it is reckoned that an extra 1350MW will be used to charge for 2 million EVs by the wind power generation in New Zealand [21]. Furthermore, the overloading of the grid is exacerbated by the trend toward increasing battery capacity [22]. Based on this limitation, V2G (vehicle-to-gird) technology has been proposed as a solution. Figure 2 illustrates the working principle of V2G technology. It means that electricity can be transferred from EV to the grid, making the power transmission more flexible and EVs can use excess electricity in batteries to ease the problem of oversupply on the grid at the peak time. However, this technology still has many constraints currently. On the one hand, this technology causes the batteries to be charged and discharged much too frequently, potentially causing severe degradation and a significant reduction in battery lifespan. On the other hand, this technology

is still in its preliminary stage and is very costly, hence it is difficult to become a reality in a short term.

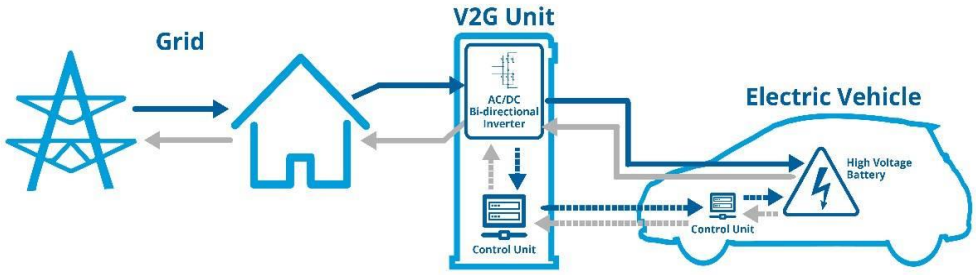

Figure 2. Schematic of V2G technology [23].

4.4. Recycling challenge

The development of transportation electrification will greatly increase the demand for lithium-ion batteries, and how to deal with waste lithium batteries has become an obstacle. A large number of metal resources are required for the manufacture of Lithium batteries, so it is involved in resource depletion and environmental problems caused by mining. On the one hand, it is stated that 500,000 gallons of water are used to exploit 1 ton of lithium which is a large consumption of water resources. On the other hand, the mine lithium has caused problems with vegetation reduction and the growth of daytime temperature in the Atacama salt flats of Chile. Hence, the recycling of Lithium batteries should be considered in order to aggravate these problems. The challenge is that Lithium batteries are difficult to recycle, because they are commonly larger and heavier, with more sophisticated structures, and are prone to cause fire and explosions if handled improperly. They are usually classified and gone through discharged, deactivated, disassembled and divided for pre-treatment, and then are sent to the recycling process. Figure 3 illustrates three classical recycling approaches, including direct, pyrometallurgy and hydrometallurgy ways [24]. Some steps are not shown by abbreviation, the actual processes are more complicated. In addition, the cost of lithium battery recycling is quite expensive, even higher than the cost of mining more lithium to manufacture new batteries, and the value of the recovered products is trivial. According to this, there are only approximately 5% of lithium batteries are recycled all around the world [25].

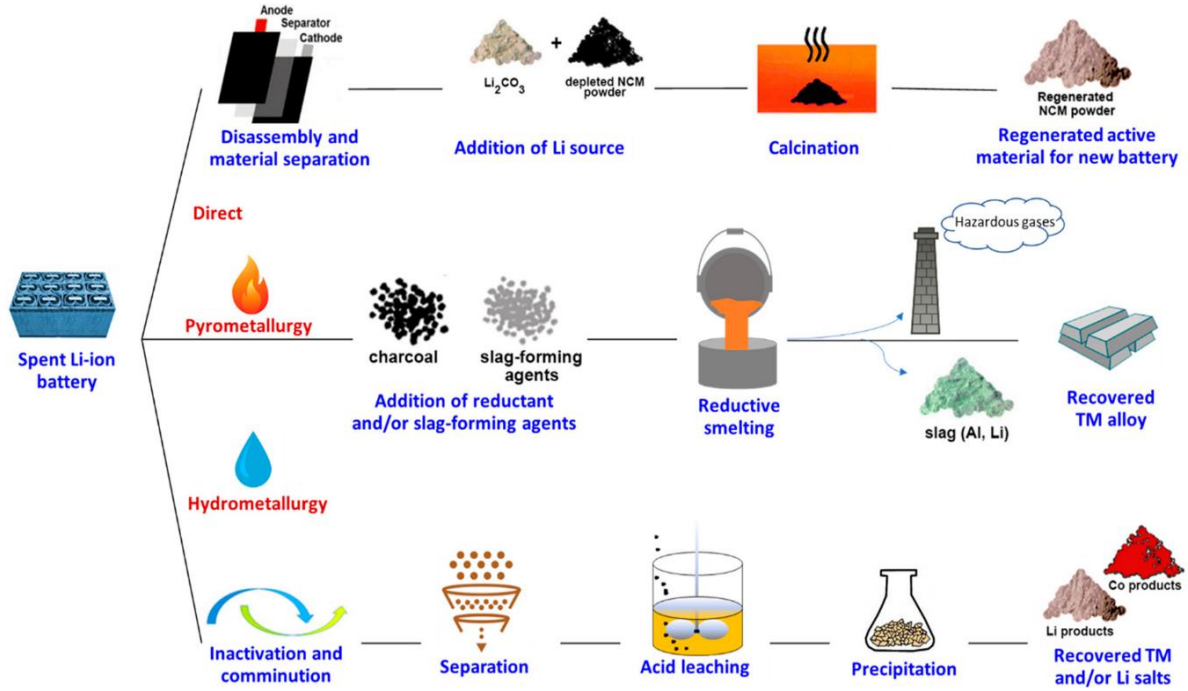

Figure 3. Typical methods for recycling spent lithium-ion battery [24].

5. Conclusion

Nowadays, environmental concerns have to be considered as global warming is becoming more and more severe due to the high level of carbon dioxide emissions, and human beings are facing the problem of resource depletion in the meantime. Hence, mankind demands the development of transportation electrification. This report concentrates on the pros and cons of transportation electrification. Electrification of transport has numerous benefits. Good properties of electric machinery make EVs more powerful; using electricity could not only reduce emission of greenhouse gases, but also save customers' money; charging EVs properly could optimize the electric system. EVs have great potential to replace the ICE cars in many situations. Nevertheless, there are still some constraints including range anxiety, battery safety issues and the burden of large-scale EVs on the Nation Grid which are discussed in this report. In response to these imperfections, the following recommendations can be considered as priorities for the future research:

The performance of lithium-ion batteries and their capacity density should be increased while safety is ensured.

A widespread charging stations network should be established to improve charging convenience and EV owners would be much easier to get rid of 'range anxiety'

The burden on the grid during peak demand periods is eased, and approaches to reduce the cost of V2G technology should be found.

The purpose of this paper is to give a concrete analysis of the two sides of transportation electrification and to provide some reference for the future development in this domain.

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