Department of Mechanical and Aerospace Engineering

A Feasibility Study on Utilising High-Performance Lithium-ion Capacitor as Main Power Source for Electric Lorries

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Abstract

Although multiple measures, regulations and technologies have been implemented to minimise GHG emissions from road freight transports, the GHG emissions from road freight activities still continues to increase and it could reach 8billion metric tonnes by 2050 (1), (2). This thesis investigates the feasibility of using high-performance Lithium-ion Capacitor (LIC) as potential main power source for electric lorries and evaluates the technologies that may catalyse the process of electrification of goods vehicles.

The overall aim is to reduce GHG emissions from road freight sector and to assess the concept of using LIC battery system as main power source for Battery Electric Lorries (BELs). Vehicle energy consumptions and battery capacities required for Light Goods Vehicle (LGV), Medium Freight Vehicle (MFV) and Heavy Goods Vehicle (HGV) are initially calculated. Through comparisons with literature values, the results are verified and assessed for feasibility evaluation. The calculations have indicated the LIC battery systems would weight approximately 1.53t, 2.45t and 4.45t for LGV, MFV and HGV respectively. Vehicle parameters that may affect the outcome of the study are also analysed and discussed.

Impacts of electrification of goods vehicles on GHG emissions from road freight sector and the energy demand in the UK and the EU are studied and evaluated. The charging of BELs is estimated to equivalently powering 3000 houses in the UK. This indicates that the UK government needs to ensure sufficient energy generations and appropriate infrastructures such as transformers and cables for the high-power requirement from recharging BELs. Such implementation and upgrades would require significant amount of financial investment from the government to be feasible.

The discussion considers the infrastructures required to recharge the electrified goods vehicles. In addition, various charging technologies are studied and evaluated for their feasibility to optimise the technical feasibility and operability of BELs. The weights of LIC battery systems may be technical feasible, however it is important that this technology is still in early development stage and requires significant amount of time to develop and be implemented. Furthermore, overhead catenary and dynamic inductive charging systems may further reduce the battery weights, however they require significant amount of investment to be implemented.

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I would like to express my appreciation to my project supervisor Mr. Cameron Johnstone, who supported my project with valuable inputs and answering my questions patiently and comprehensively. Further thanks are reserved for Dr. Paul Tuohy, who has been really helpful throughout the course by providing constructive inputs and advice for the course. His feedback has allowed me to proceed the course, and eventually my individual and group projects with confidence.

I also would like to thank Dr. Deepak Dubal at The University of Adelaide. He is the one who inspired me to commence my studies in Sustainable Engineering and ultimately my research in Lithium-ion Capacitor. I am extremely grateful for his supports and inspirations to make me who I am today. Lastly, I would like to thank my parents who have been supporting my studies overseas for the last 6 years and their immense emotional supports to me throughout the difficult times.

"I think it is possible for ordinary people to choose to be extraordinary." (Musk, 2017)

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List of Abbreviations

AC	Activated Carbon
AMT	Automated Manual Transmission
BEL	Battery Electric Lorry
BEIS	Department Business, Energy & Industrial Strategy
BEHGV	Battery Electric Heavy Goods Vehicle
CRGO	Chemically-Reduced Graphene Oxide
CO	Carbon Monoxide
CVT	Continuously Variable Transmission
C-LTO	Carbon Coated Lithium Titanate
DCPC	Driver Certificate of Professional Competence
DOD	Depth of Discharge
DfT	Department for Transport
EDLC	Electrical Double Layer Capacitors
EV	Electric Vehicle
EVWPT	Electrical Vehicle Wireless Power Transfer
FRGO	Flash-Reduced Graphene Oxide
GHG	Greenhouse Gas
GLA	Greater London Authority
GVW	Gross Vehicle Weight
G-LTO	Graphene Coated Lithium Titanate
HC	Hard Carbon
HESS	Hybrid Energy Storage System
HEV	Hybrid Electric Vehicle
HGV	Heavy Goods Vehicle
ICE	Internal Combustion Engine
IM	Induction Motor

IPT	Inductive Power Transfer
KPI	Key Performance Indicator
LGV	Light Goods Vehicle
LIB	Li-ion Battery
LFP	Lithium Iron-Phosphate
LTO	Lithium Titanate
Li-S	Lithium-Sulphur
Li-air	Lithium-Air
MC	Mechanical Commutator
MFV	Medium-Freight Vehicle
NOx	Nitrogen Oxide
NO_2	Nitrogen Dioxide
PM	Particulate Matter
PMBM	Permanent Magnet Brushless Motor
PMSM	Permanent Magnet Synchronous Motor
PRGO	Partially Reduced Graphene Oxide
PIHEV	Plug-In Hybrid Electric Vehicle
rGO	Reduced Graphene Oxide
RTFC	Renewable Transport Fuel Certificate
SAFED	Safe and Fuel-Efficient Driving
SRM	Switched Reluctance Motor
SOC	State-of-Charge
SOx	Sulphur Oxide
TfL	Transport for London
TiO_2	Titanium Dioxide
VOC	Volatile Organic Compound
WPT	Wireless Power Transfer

1 Introduction

1.1 Background

The 2008 Climate Change Act sets a legally binding target to reduce the emissions of greenhouse gas (GHG) in the UK by at least 80% prior 2050. This is to address the issues of climate change that has risen politically and socially at an astonishing rate over the last 5 years. In addition, the UK government also sets to continue to improve the air quality by limiting the concentrations of major pollutants such as particulate matter (PM10 and PM2.5) and nitrogen dioxide (NO_2) (1). Hence, all efforts are resorted to decarbonise the generation of electricity and heating, to direct more investment in renewable energy and to improve the energy efficiency of residential housings and commercial buildings. However, the emissions of GHG from road transportations has been a more urging issue due to the growth of city populations and the number of vehicles.

Since the introduction of electric vehicles (EVs), the public has been encouraged by the government with various subsidies and tax exemptions (3), (4). Consequently, the number of electric vehicles on the road has been increasing drastically. The International Energy Agency has estimated the number of electric vehicles will reach 125 million by 2030 based existing and announced policies and subsidies. The agency also estimated there is potential for the number of electric vehicles to reach over 200 million if the governments increase their ambitions in line with international climate change goals (5), (6).

The road freight networks have been acting as the arteries for global economic activity due to its representations of globalisation and economic development within the country. As a country continues to develop its economy, the comprehensive level of infrastructure, the demand of goods and ultimately the freight logistics will increase. In the UK, Heavy Goods Vehicles (HGVs) are currently estimated to account for approximately 17% of UK GHG emissions from road transport and approximately 21% of road transport nitrogen oxide (NOx) emissions (1). Freight lorries are considered as significant sources of air pollutants such as particulate matter (PM10, PM2.5), Nitrogen Oxides (NOx), Carbon Monoxide (CO), Sulphur Oxides (SOx) and Volatile Organic Compounds (VOC). These air pollutants can pose adverse effect on air quality and human health (7). Hence, the electrification of public transport and small vehicles have acquired immense amount of attentions from the vehicle corporations and the government.

Electric HGVs are relatively new innovation and its development has been stagnant due to high energy requirement and low energy density of batteries (8). However, with the recent advancement of battery technology, battery electric HGVs are finally being made technically and financially feasible (9). In addition, the battery prices are expected to continue to decrease significantly which would crucially improve the life cycle costs of electric HGVs (8), (10). As a result, more vehicle manufacturers are starting to introduce full battery HGVs with significant travel range, varies from 100km to 800km (9). Similarly, the development of battery technology has been a continuous breakthrough due to its potential as a viable energy storage in renewable energy generations as well as in EV and Plug-In Hybrid Electric Vehicle (PIHEV) applications (11).

Lithium-ion Capacitor (LIC) is a high-performance hybrid energy storage device, a combined energy storage device of Supercapacitor (SC) and Lithium-ion Battery (LIB) (11), (12), (13). SC can be classed into two types based on the chemical reactions to store energy. Electrochemical Double Layer Capacitors (EDLCs) store energy by reversible ion adsorption, whereas Pseudo-capacitors store energy by fast surface redox reactions (13). The mechanism of EDLCs offers high power density and long lifecycle but low energy density. LIC inherits the high-power density from SC and the high-energy density from LIB as the anode of LIC function as LIB electrode and the cathode functions as SC electrode (13). Moreover, its ability to operate at wider temperature range (-30ºC to 70ºC) and higher maximum voltage (3.8V) would decrease the cost and loss of the converter significantly (14). Consequently, LICs have emerged as one of the most promising candidates for next generation electrochemical energy storage device (11) , (12), (13), (15), (14), (16). In addition, LICs are believed to be the suitable energy storage device for hybrid and all-electric heavy duty vehicle systems (12), (13), (16), (17), (18), (19).

1.2 Project Objectives and Scope

This thesis aims to assess the feasibility of using LIC as power source for road freight transport vehicle systems such as 3.5 tonne LGVs, 15 tonne MFVs and up to 44 tonne HGVs.

The main objectives of this project are:

- Determination of the energy and the power required to move the vehicles for designated range and duration
- Design and size the volume and the mass of LIC required for the vehicles
- Investigation on the performances and technical feasibility of the battery system on the vehicles
- Evaluation on alternative technology and infrastructure required to optimise the performances of full electric road freight transport and logistics system

This project is to evaluate the potential applicability of LICs on light and heavy goods vehicles in the attempt of electrification of road freight transport and logistics system. As multiple vehicle manufacturers introducing full battery HGVs with various range and load capacity, this report also aims to investigate the efficiency and the technical improvement can be brought in by LICs as the replacement of LIBs. The electrification of road freight transport and logistics system is expected to significantly reduce carbon emissions from land transport and its reliance on fossil fuels. Ultimately, reduction on the release of air pollutants such as PM10, PM2.5, NOx, SOx, CO and VOC, which have adverse effects on air quality and human health in the region.

This project will not evaluate any detailed economic aspects due to unpredictable cost of such relatively new and unmatured technology in the market. Additionally, this project will not investigate any mechanical and electrical design of the battery system on the vehicles as this paper is dedicated to the feasibility study of LIC on battery electric LGVs, MFVs and HGVs.

1.3 Methodology

Literature Review

- Current Lithium-ion Capacitor State-of-the-art
- Research on the development of Lithium-ion Capacitor
- The development of electric lorries
- Research on the electric lorries that are available on the market

Size and Design of The Battery Systems

- Calculations of powers required and energy consumptions of the lorries
- Comparison of the theoretical results to literature
- Calculation of the mass and volume required of the battery systems for the lorries
- Investigation on the size and mass of LIC system on the vehicles

Analysis and Evaluation

- Results modelling and analysis
- Assessment of the impacts on energy demand
- Evaluation on the establishment of infrastructures required
- Evaluation on alternative power charging technologies

Discussions and Conclusion

- Evaluation on overall performance of battery system
- Possible challenges in implementations
- Conclusion and future work

Figure 1: Project Methodology (Source: Own Design)

The first section of the thesis is to provide insights on Lithium-ion Capacitor state-of-the-art and its development regarding to its electrode materials and structural design. In addition, the development of electric lorries is provided for fundamental understanding on current development perceptions prior conducting further investigations.

The following chapter provides the sizing and the design of battery systems for the electric lorries. It consists of the calculations to determine the power required for desired acceleration and energy consumptions for the electric lorries to operate at designated conditions. Furthermore, the calculations results are compared to literature values from other studies and undisclosed information from vehicle manufacturers.

The third chapter is analysis and evaluation of the results. In this chapter, feasibility study is carried out to assess the practicability of the mass and volume of the battery systems for the electric lorries. The results are discussed and verified by comparing them to literature values. Subsequently, feasibility and validity of the results are evaluated and summarised.

The fourth chapter mainly discusses the influences of vehicle parameters such as vehicle materials, aerodynamics drag coefficient and rolling resistance coefficient on capacity and weight of the battery system. In addition, the impacts of electrification of goods vehicles on GHG emissions from road freight sector and electricity demand in the UK are analysed and discussed. Moreover, the infrastructures required to recharge BELs and the challenges to implement alternative charging technologies to establish a comprehensive electricity supply system in the UK are evaluated.

The final chapter concludes the technical feasibility study on Lithium-ion Capacitor as main power source for goods vehicles. Lastly, a detailed discussion is also included to evaluate the future work required for a successful project realisation.

2 Literature Review

2.1 Transport and Logistics Systems

2.1.1 Carbon Emissions from Transport and Logistics Systems

Lorries are an important part of modern road freight transport and logistics systems which also represents as key enabler of global economic activity in the country. In 2015, the road freight sector has contributed approximately £11.9 billion, which is comprised by more than 44,500 road freight enterprises with a total of more than 250,000 employees (1), (20). In 2017, there were approximately 1.4 billion tonnes of goods lifted via domestic road freight and 18.6 billion kilometres of distance were travelled by HGVs in the UK (20). This ultimately contributed equivalent 20 million tonnes of carbon dioxide to the atmosphere (21). Figure 2 has shown that 16% of UK GHG emissions from domestic transport are from HGVs despite HGVs made up just 5% of vehicle miles (1). In addition, HGVs currently account for approximately 21% of UK road transport NOx emissions.

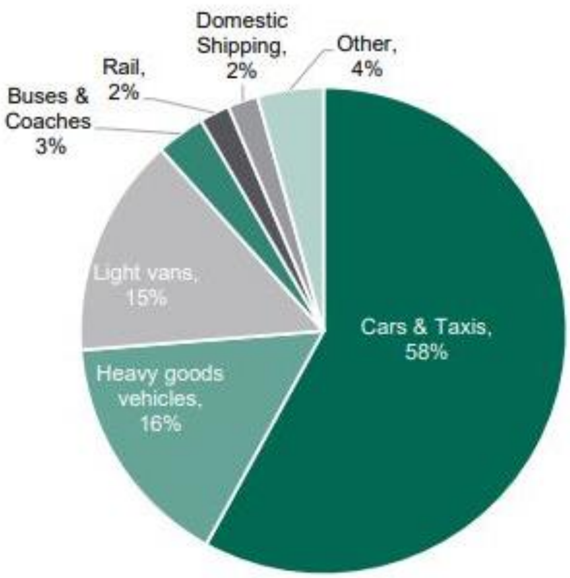


Figure 2: GHG emissions from the transport in 2014 (1).

Based on vehicle duty cycles, long haul delivery between national and international sites is responsible for approximately 45% of GHG emissions while regional delivery is contributing at least a quarter of HGVs' GHG emissions.

Department for Business, Energy & Industrial Strategy (BEIS) has estimated that HGV carbon emissions will drop gradually out to 2025 due to incremental improvements in fuel efficiency. However, BEIS acknowledged that the carbon emissions from HGVs may continue to hinder the effort of the UK government on meeting climate change targets within the road freight sector if no further actions taken (1) (22). Furthermore, BEIS projected that the emissions from the road transport will increase after 2025 as HGVs travel distance continues to increase due to the rise of economic activities (22). Consequently, The UK Government is considering additional measures to meet legal limits for NOx and GHG. However, such effort can be depreciated due to significant rise of GHG emissions from the road freight globally due to inevitable increase in economic activity in developing countries. In China, the road freight activity has increased by more than 30-fold since 1975 (23). Similarly, road freight activity in India has increased by more than 9-fold over the same period (24). The European Commission's Reference Scenario predicted the transport demand will continue to increase, which may result in observed historical high in GHG emissions, due to stagnant improvements on fuel efficiency of the new HGVs (25). Figure 3 below has shown that the projection of GHG emissions from road freight activities may reach 8billion metric tonnes.

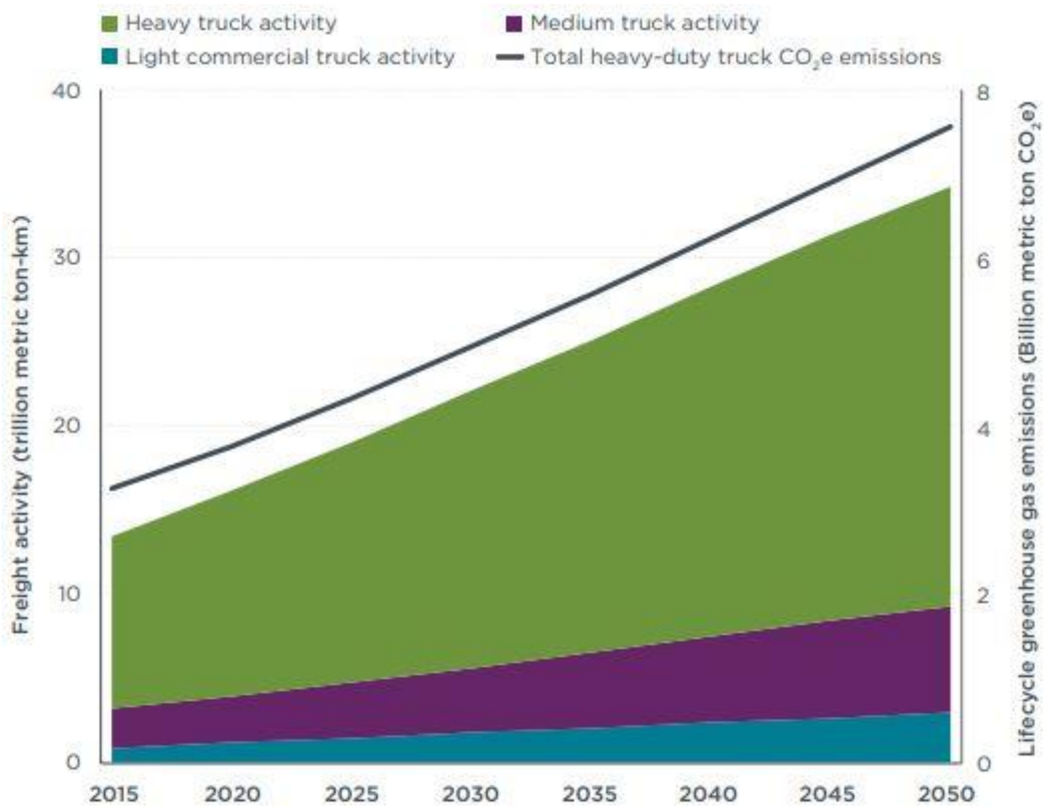


Figure 3: Projected Global Freight Activity and Lifecycle GHG emissions until 2050 (2).

As the road freight activity is closely related to the economic growth of a nation, particularly being driven by globalisation of production activities, urbanisation and rapid industrialisation, the electrification of road freight transport and logistics systems may seem inevitable and necessary in order to tackle climate change and air pollutions (9), (24).

2.2 Current Policies and Measures to Reduce Carbon Emissions from Road Freight Sector

2.2.1 Efficient Driving and In-Cab Technologies

"Efficient driving", also known as "eco-driving" is a term to describe the energy efficient operation of vehicles without compromising the safety, responsibility and anticipatory driving techniques of driving a vehicle. It is designated for the drivers to drive the vehicles in more sustainable way to improve fuel efficiency, road safety and to reduce the emissions of GHG (1). It is believed that the decisions on operational level (driving style) have a significant influence on fuel consumptions. Efficient driving is estimated to improve the fuel efficiency of the vehicles from 5% up to 62%, depending on car type, route and benchmark (26), (27).

The techniques of eco-driving can be summarised as:

i. Moderate acceleration with optimal gear changing (typically shifts up to 2000 and 2500 rpm)

ii. Allow a safe distance with other vehicles and anticipating traffic flow and indicators to avoid harsh braking and acceleration

iii. Appropriate vehicle speeds with steady driving pace

iv. Avoid excessive idling

In the UK, HGV drivers receive their training for eco-driving techniques from the Driver Certificate of Professional Competence (DCPC) and Safe and Fuel-Efficient Driving (SAFED), which required refresh training every 2 years (28).

Table 1 has shown the summary of evaluation of eco-driving training in other countries to improve fuel efficiency of road freight sector and to reduce the emissions of GHG. In addition, driver monitoring systems are installed in the HGVs to assist the drivers in safe and fuel efficient driving by monitoring the driving patterns such as harsh braking, acceleration and over speeding as Key Performance Indicators (KPIs) (1), (28).

Telematics systems are widely employed by road freight companies to monitor fuel efficiency (1), (28), (29). In general, this will improve the effectiveness of HGVs efficient driving programs by ensuring long-term eco-driving behaviours and ethics to maintain fuel savings benefits and road safety practices (29). Since its introduction in 2005, efficient driving has successfully improved the fuel efficiency of HGVs by 7%, which is approximately 5% of fuel and GHG saving (1). However, the results are expected to change with wider employment of driving monitoring systems due to larger sample size data and larger number of hauliers surveyed (1), (28), (29).

Year	Country	Training method	Evaluation setting	Number of drivers	Fuel economy improvement
2005	UK	Driving simulator	Driving simulator	>600	3.5% immediately after training
2007	US	Class	Closed driving course	36	33.6% to 40.5% immediately after training
2009	Australia	Class	Prescribed real-world route	12	27.3% immediately after training; 26.9% after 3 months
2010	European countries	Class followed by monthly feedback and regular refreshing class	Actual real-world routes	322	9.4% over an unknown period
2011	U.S	Individualized coaching and in-vehicle real-time feedback system	Actual real-world routes	695	13.7% after 2 months
2013	Japan	Class	No information available	~3,000	8.7% immediately after training
2014	US	Individualised coaching and in-vehicle real-time feedback system (plus financial incentives)	Actual real-world routes	46	2.6% (5.4% with financial incentives) for sleeper cabs and 5.2% (9.9% with financial incentives) for day cabs after two months

Table 1: Summary of HGV efficient driving evaluation studies (29)

2.2.2. Improvements on Vehicle Design

There has been a steady flow of technology refinements to improve the fuel efficiency of HGVs (30). Fuel efficient technologies such as aerodynamics devices and profiling, low rolling resistance tyres, reduction on the vehicle tare weight and predictive cruise control have offered operators cost effective options for fuel savings and GHG emissions (1), (30). Figure 4 below summarises the current available technologies and measures that can be employed to improve the fuel efficiency of HGVs and ultimately to minimise GHG emissions from road freight sector.

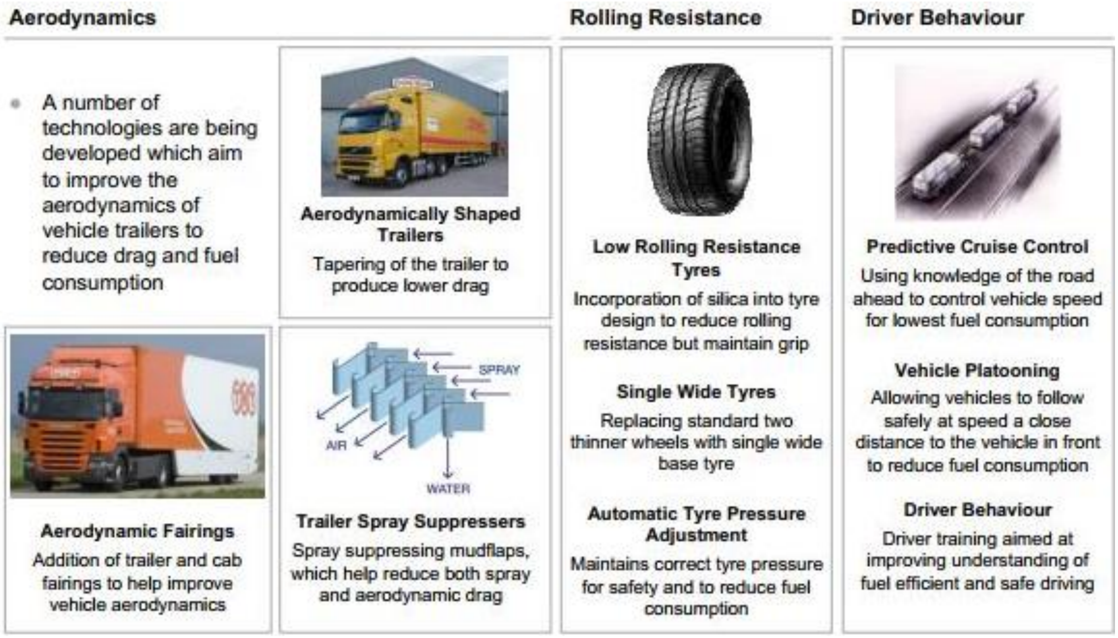


Figure 4: Technologies lie in the fields of improving aerodynamics, reducing rolling resistance and driver behaviour (31).

HGVs are widely considered as aerodynamically inefficient in comparison to other land vehicles due to their un-streamlined body shapes (32). When a vehicle moves, its surrounding air exerts a drag force on the vehicle that opposes its motion, this is knows as aerodynamic drag force. It is dictated by vehicle shape, frontal area and the speed of vehicle. A streamlined body shape helps to obtain a low value of drag which can significantly reduce power consumed, especially at high speeds (1), (33). In general, the mileage of HGVs can vary from 130,000 km to 160,000 km, hence any reduction on aerodynamic drag force will provide significant fuel savings and reduction of GHG emission from the road freight sector (32). To date, there are several features such as roof deflectors, roof fairings, cab side-edge fairings, cab collars, tractor side panels, filler panels, trailer side panels and aerodynamic trailers can be retrofitted to existing HGVs to improve their aerodynamics (1), (32).

In addition, low rolling resistance tyres are developed to improve the fuel efficiency of land vehicles (1), (34), (35). Rolling resistance is an energy loss caused by the interaction between a rolling tyre and the road surface. Hence, low resistance tyres are designed to minimise the rolling resistance of a tyre whilst maintaining the required levels of grip on the road by incorporating silica into the tyres (1), (35), (31). Though the design of low rolling resistance tyres requires satisfactory road conditions, soil parameter and the pressure of the tyres, the research of the tyres were quantified and modelled to minimise the rolling resistance of the tyres (34), (35). Likewise tyre pressure monitoring systems are employed to perform regular check on the tyre pressure for road safety practices and for the reduction of fuel consumptions. Such system is also known to be beneficial in EVs to minimise power consumption and to maximise travel range of the EVs (35), (31).

Furthermore, multiple vehicle manufacturers have been striving to improve the thermal and mechanical efficiency of the vehicle engine. Engine efficiency is believed to have significant influences on minimising fuel consumption and improving overall HGV fuel efficiency (1). However, only approximately 15% of fuel energy is used to move the vehicle or to run its accessories. The main losses are in the engine and driveline and by vehicle idling as the engine continues to run even though the vehicle has stopped (36). Internal Combustion Engine (ICE) in the vehicle is account for over 60% of the energy losses as the engine converts chemical energy from the fuel to mechanical energy. Significant amount of energy losses in this conversion due to internal friction, aerodynamic loss in pumping air through the engine, and waste heat. In addition, vehicle accessories such as air conditioning, power steering, windshield wipers and others are powered by the engine, which also significantly reduce the engine efficiency (24), (36), (37). However, the introduction of waste heat recovery systems for the ICE vehicle has significantly improve the efficiency of the engine, as the systems are able to convert the engine thermal losses into energy as supplement power to the vehicle. Moreover, improvement on transmissions can greatly increase the fuel efficiency by optimising gear ratios and the matching of rear axle. It is estimated transmission technologies such as Continuously Variable Transmission (CVT) and Automated Manual Transmission (AMT) can increase the fuel efficiency of the vehicle by 3% to 8% and 7% to 9% respectively by ensuring optimum shift points (24), (31), (36).

2.3 Decarbonisation and Electrification of Road Freight Transports

Though efforts are put in to decarbonise road freight transportation by introducing new technologies to improve the fuel efficiency of HGVs and to minimise the carbon emission from the vehicles (1), (24),. However, it is evident that with the rise of economic activities around the globe due to globalisation, rapid industrialisation and urbanisation, the demands for road freight transportation will continue to rise. Consequently, this will result in higher GHG emissions in road freight sector and hinder our efforts in tackling climate change (9), (24). Alternative fuels such as gasoline, diesel, biodiesel, liquified petroleum gas and hybrid diesel are also considered to improve fuel efficiency of HGVs and to minimise GHG emissions from road freight sector (1), (36).

In addition, policies have been implemented to adopt Climate Change Act in 2008 as the UK government is set to reduce its carbon emission by 80% prior 2050 (1), (38). In 2007, the Greater London Authority (GLA) launched Climate Change Action Plan which contains a series of policies and measures which aim to minimise GHG emissions in London. This action plan is expected to limit the emissions of carbon dioxide in the city to 600 million tonnes in 2025 (39). In 2019, Freight and Servicing Plan was introduced by Transport for London (TfL), and London is committed to being zero carbon by 2050 (40). Moreover, Renewable Transport Fuel Obligation (RTFO) is introduced in the UK to encourage the use of biofuels. The RTFO requires refiners, importers and any other suppliers who supply more than 450,000 litres of transport fuel per year to the UK market to redeem a number of Renewable Transport Fuel Certificates (RTFCs) in proportion to the volume of fossil fuel they supply in the country (1), (41). However, it is evident that the supply of biomass is not able to meet 20% of total vehicle fuel consumption globally (42). Moreover, various studies have concluded that current biofuels policies in EU may result in higher GHG emissions due to indirect land use change (43). Therefore, the focus has been shifted to hybrid/full electrification of HGVs due to recent advance development of energy storage technology as previously maximum commitments were on improving fuel efficient road freight vehicles and improving logistics and operational efficiency (24).

The electrification of road freight transport will certainly increase the total energy demand and hence the burden of the grid. It is estimated that a single truck charge of 1MWh would be equivalent as supplying one-third of annual electricity to an average household in Europe. In addition, fast charging with a 1MW connection to a Battery Electric Lorry (BEL) would draw approximately 3000 to 4000 average houses in the UK per charge (43). With a full fleet of BEL operating on the road, the increasing demand will certainly pose some issues on the grid and energy generation capacities. Furthermore, the distribution networks of electricity may require major investment to upgrade on the areas where only low voltage network is available. Without appropriate planning and mitigation measures, the charging of a BEL may overload local electric network and lead to power outages. It has been tested that over 300,000 UK networks may be at risk of overloading from EV charging, particularly in rural areas which have low resilience electricity distribution network (6). Hence, the electrification of road freight transportations will certainly require appropriate charging strategies and Demand Site Management such as smart charging management plans and standardisation of charging infrastructure (6), (43). Evidently, the cost of infrastructures is the main hinderance to transition of electrifying our land transport systems. Without appropriate and comprehensive charging system in place, the electrification of road freight transportations will be slow and ineffective (6), (43), (44).

Soon after, hybrid/full electric HGVs was introduced by using hydrogen fuel cells technology. However, such technology has been proven to be too expensive due to high infrastructure investment costs and hydrogen storage (24), (42). In addition, hydrogen fuel cell technology is considered inappropriate for heavy power applications due to long start-up times, slow response to changed power requirement and technical difficulty to install hydrogen storage onboard the vehicle (36). Furthermore, the overall efficiency of a hydrogen generation and distribution system is estimated to be around 20% which is substantially lower than ICE engines that typically have the efficiency around 40% to 45% (42). Ultimately, hydrogen fuel cell technology was soon fallen out of considerations as an alternative power source for HGVs (42).

Hybrid drivetrain is one of the popular candidates as alternative power source to replace ICEs in HGVs. It is estimated that hybrid drivetrain technology could improve fuel efficiency of a vehicle up to 30% (42), (45). In addition, the hybridisation of HGVs can lower the NOx emissions by 31% by improving the thermal conditions in the exhaust system during braking and idling. However, it is acknowledged that hybrid drivetrain technology is not an appropriate alternative power source for long-haulage heavy vehicles.

As the experimental results in Figure 5 have indicated that hybrid drivetrain has substantially smaller engine displacement volume, peak power, and weigh classification than ICE vehicles, which result in 22% higher carbon dioxide emissions in long distance delivery (46). Furthermore, hybrid drivetrain requires well-designed and complex control systems in the vehicle. Such complex control systems can be technically challenging in order to utilise the potential benefits of hybridisation, otherwise the systems may fail to perform in maximising fuel efficiency and reducing GHG emissions (45), (47), (46).

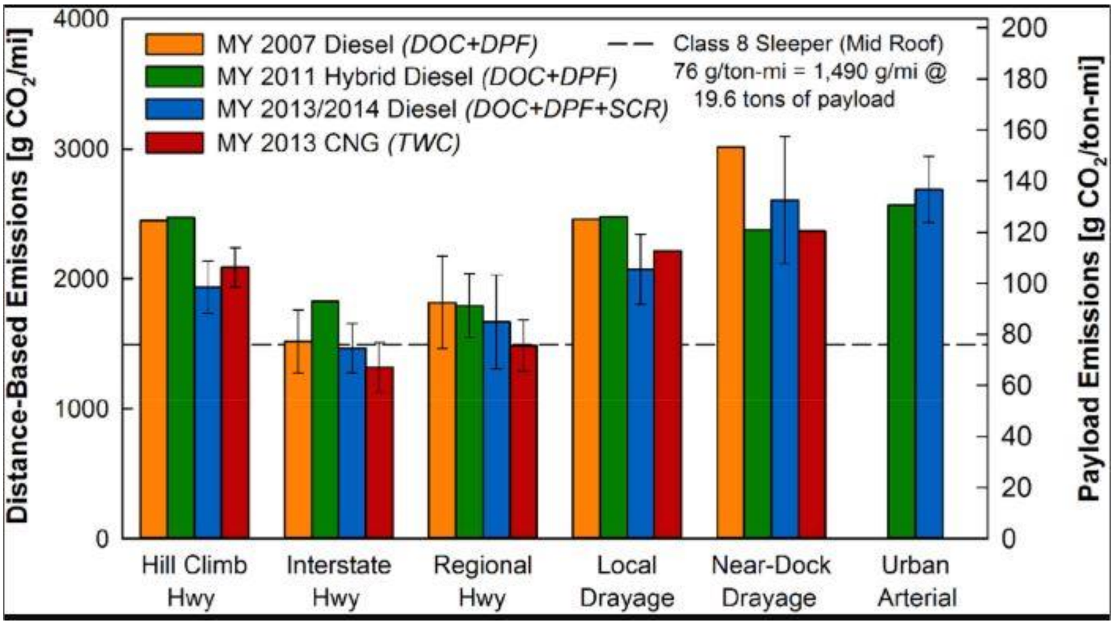


Figure 5: Carbon emissions from various HGV groups and their travel route (46).

2.2.3. Battery Electric Lorries (BELs)

Deep carbonisation of road freight transportations is considered challenging as it requires high investment costs for infrastructures and appropriate technology to accommodate the additional power demand from the electrification of the sector (42). However, there is enormous interest in the development of BEL due to recent breakthrough in battery technology. This breakthrough would allow a BEL to have a travel range up to 800 miles. BEL was first introduced as garbage trucks in China for the preparation of Beijing Olympic 2008 due to their predictable travel routes and “stop and start” operation. In addition, it was later transformed to urban bus fleet in Shenzhen, China where more than 160,000 electric bus were deployed in the city (25), (48).

Enormous speculations and interests have been raised on BEL since the announcement from Tesla to introduce long haul BEL in 2021 (49), (50). Soon after, other vehicle manufacturers such as Mercedes-Benz, Freightliner and BYD introduced their own version of Battery Electric HGVs (BEHGVs) with minimum range of 200km (9). However, such announcements have yet to convince the public as with the current LIB technology, a BEHGVs with the range of 600 miles would weight over 18 tonnes (49), (51). EVs that are driven by electric motors have high efficiencies of more than 90% as electric motors are not affected by the driving profiles, whereas ICEs are converting significant amount of energy to heat by braking, thus its operating conditions would fall to suboptimal. The energy consumption of a typical ICE goods vehicle would be around 3.33kWh/km for the average route and 4.70kWh/kg for the heavy route (52). Hence, BEHGV was soon revolutionised by various vehicle manufacturers, which ultimately becoming more popular in vehicles market (25), (44), (53). As aforementioned, technologies such as hydrogen fuel cells and hybrid ICEs would require at least 3 times more electricity than a full electric drivetrain (25).

EVs may have been well developed with current LIB technology, however it has been proven to be challenging for HGVs application. This is mainly due to the differences in design requirements and priorities, HGV can weight heavier by 4-folds than standard EV and hence it has substantially high energy requirement in comparison to EVs (9), (54). The volume and the amount of the battery cells in HGVs are significantly greater than that of typical EVs.

There are five parameters that have been used to examine the suitability of batteries for HGVs application:

1. Energy to weight ratio
2. Energy to volume ratio
3. Power to weight ratio
4. Battery lifetime
5. Charging time

The high requirements have urged better designs and improvements for HGVs with lower rolling resistance tyre and coefficient of drag, lighter materials to maximise payload, and energy denser battery (36), (49). Additionally, new technologies are developed to extend the range of HGVs such as integrated hydrogen fuel cell to recharge the battery or to power their wheels on the move (1).

2.3.2. BEL Market Potential

As the development of battery technology is becoming more mature and advance, the conditions for BEL development have been significantly improved. The price of battery has dropped by approximately a factor of 4, from US$750 to US$1000 per kWh to US$150 to US$300 per kWh (25), (49). In addition, the energy densities of LIB have been improved from 110 Wh/kg to approximately 250 Wh/kg, this ultimately allows the development of BEL to be less technically challenging (25). These improvements have allowed BEL to be technically and financially viable. In addition, the rise of environmental awareness and sustainability ideology in our societies and politics have greatly improved the potential of BEL in the road freight transport markets (1), (5), (44). As a result, the German government announced numerous subsidies and financial incentives to encourage the use of BEL or low carbon emissions vehicles, such as tolls exemptions on German highway and lower vehicles tax. However, the financial incentives are currently less effective than expected due to incomprehensive charging infrastructures across the country (44). BEL requires advance charging technologies and wide-ranging of power stations to be effectively functionable, especially for long haul BEL. Furthermore, the power stations will require appropriate fast charging technology as a typical charge system may take up to 8 hours to recharge a 120kWh battery. However, current fast charging technology is facing several technical issues which may result in overheating of the battery, efficiency losses, and shorter battery lifecycle (43). These issues have been discovered to be one of the factors that hinder the penetration of BEL in road freight transport sector and its market potential (44).

2.4 Lithium-ion Capacitor

2.4.1 Current State-of-the-art

Evidently, current LIB technology would greatly restrict the payload and the gross vehicle weight (GVW) of HGVs, and the long recharging time would critically and greatly decrease the operation efficiency of road freight transports (55). Moreover, LIBs have relatively low lifecycle and high replacement cost, which make LIB powered BEHGVs less attractive in the market (12), (44). In addition, modern LIBs are designed to sacrifice their classically high cell voltage in exchange of better rate capability and cyclability (56). Hence, alternative battery technology must be considered and developed for BEHGV application (42), (49). Though the developments of LIBs and SCs have been considered successful and mature enough for wider range of power electronic applications. However, LIB is considered as a not suitable power source for large scale applications due to its relatively low power density and low lifecycle (16). These drawbacks cause significant long charging time and as a result, its application on BEL has been proven to be infeasible for HGVs operation (55). SCs have been used in various hybrid systems combining with fuel cells and batteries due to their high-power density (16). Nevertheless, SCs suffer a massive drawback that is their significant low energy density compared to LIBs. The combination of the battery-SC is known as Hybrid Energy Storage System (HESS), which possesses the advantageous and characteristics of both modules (56), (57). However, such complex hybrid architecture requires expensive and high-efficient DC-DC converter, which ultimately make HESS less attractive in EVs application where cost, weight and volume are greatly restricted (58). LIC technology is one of the well-known HESS, which is considered as a suitable alternative high-power power source technology (16), (59). Subsequently, many efforts have been diverted to developing Li-ion Capacitor (LIC) which is an electrochemical energy storage system with combined mechanisms of LIB and SC. LICs can be categorised between SCs and LIBs, it is believed that LICs can bridge the gap between LIBs and SCs (57), (60). The Ragone plot in Figure 6 has shown that LICs have higher power density than LIBs and fuel cells, and higher energy density than SC. This indicates that LICs have high energy storage and high voltage output that can be applied in high power transportation such as electric vehicles, energy storage for renewable energy plants and high-power electronic applications.

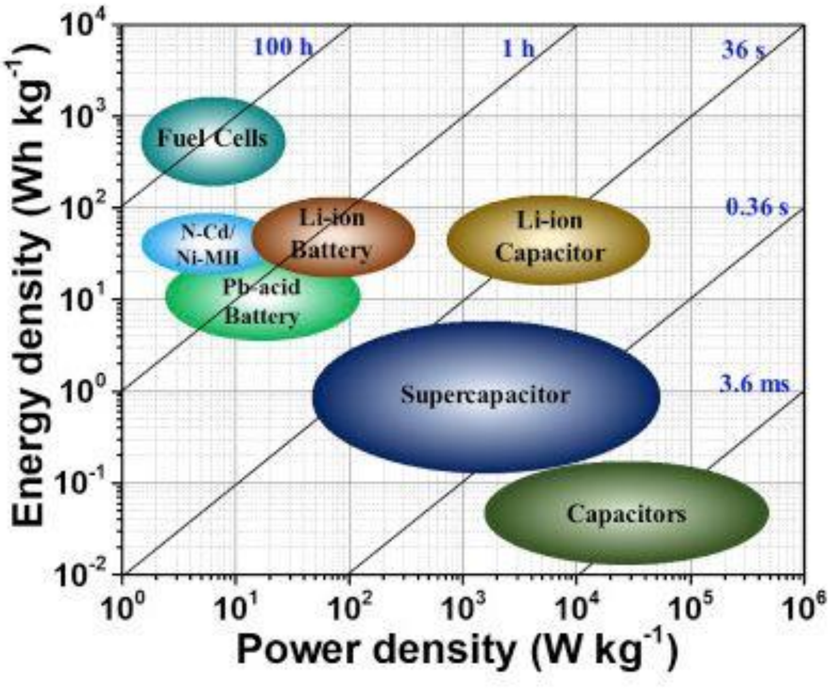


Figure 6: Ragone plot shows the demand for high power/energy electrochemical energy storage devices relative to present day technology (61).

As aforementioned, the operating temperature of LIC is ranged from -30ºC to 70ºC, which would greatly improve the resilience of battery systems in various operating conditions. In addition, its ability to operate at between 2.2V to 3.8V would allow better battery cell connection arrangement, which can simplify the complexity of the entire system as number of cells required to connect in series will be lower (58). Moreover, this advantage will allow the battery to operate through high demand period such as rapid acceleration and maintaining vehicle speed while climbing the hill, without using bulk hold-up capacitance. In general, this would offer better stability to the whole battery and operating systems. On top of that, LIC inherits its long lifecycle and high charge and discharge rate from SC. It has a long lifecycle of approximately 3000 cycles with 80% capacity retention, which is approximately 3-folds higher than most of the LIBs (13). These advantageous would make LIC a more ideal candidate than LIB as an alternative power source for BEL. As LIB's low power density would limit BEL's ability to be driven at higher speed and acceleration rate. Thus, LIB powered BELs require extreme long recharging time, typically 8 hours (43). Therefore, LIC is becoming a more popular alternative power source due to its versatility and flexibility for high power applications.

2.4.2 LIC Electrodes Materials and Its Electrochemical Mechanisms

LICs are constructed from a capacitor-type electrode and a LIB-type electrode with a nonaqueous Li-salt-containing electrolyte (11), (12), (57), (62). LIC utilises both Faradaic and non-Faradaic processes to store charges to obtain higher energy density than EDLC and higher power density than LIB without sacrificing cycling stability (16), (59). From Figure 7, the cathode of LIC functions as EDLCs where the energy is physically stored on the surface of the electrodes by adsorptions while the anode functions as LIB where lithium ion reacts with the electrode by intercalation (12). The two electrodes of LIC operate reversibly in different potential ranges with different electrochemical mechanisms offer higher operation voltage with higher energy and power densities (12), (15), (62).The energy density is mainly based on the adsorption rate in cathode. Hence, it is crucial to have high specific surface area materials, such as activated carbon, graphite and graphene, which the former two materials are widely used in the electrodes of SC and LIB (12), (13).

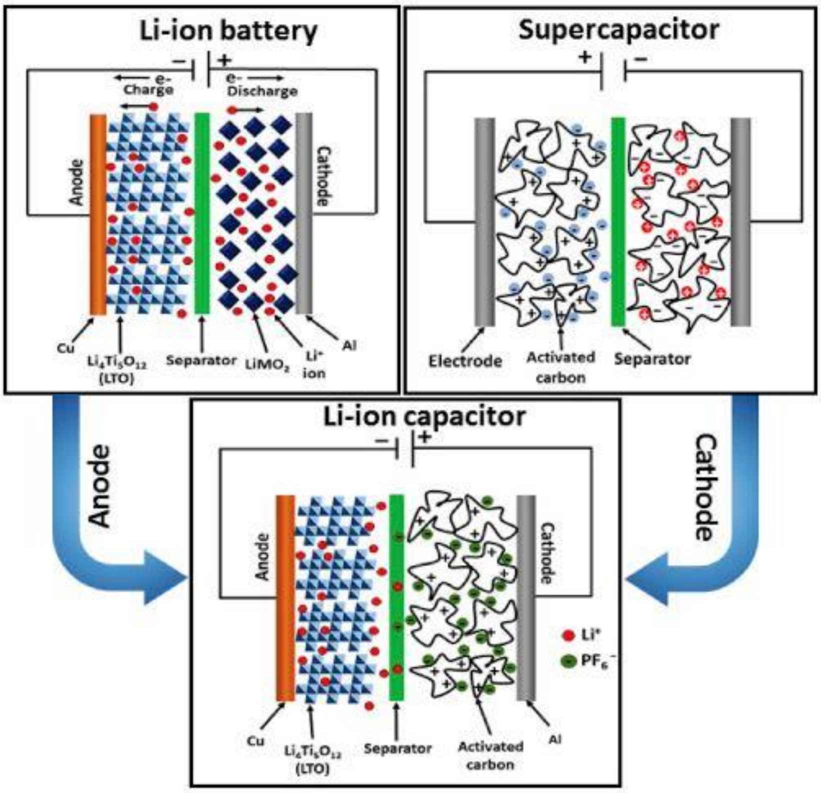


Figure 7: Electrochemical charge-storage mechanism and configurations of LIBs, SCs and LICs (61).

Figure 8 has shown the reconfiguration of AC based EDLC into LIC as second-generation energy storage. Appropriate combinations of anode and cathode materials would greatly improve the performances of LICs. Thus, it is crucial to determine the optimum mass ratio of the anode and cathode as an optimum mass balance will provide a substantial increase in the net operating potential and energy density of LICs (12). Activated Carbon (AC) is more popular and commonly used than other carbonaceous materials in EDLC and LIC due to its unique characteristics such as high electrical conductivity and chemical stability, and additionally it can be used as both anode and cathode materials (12), (61), (62). Furthermore, activated carbon is relatively cheap, easy to synthesise and more environment friendly in comparison to other materials such as metal oxides, graphite and graphene (16).

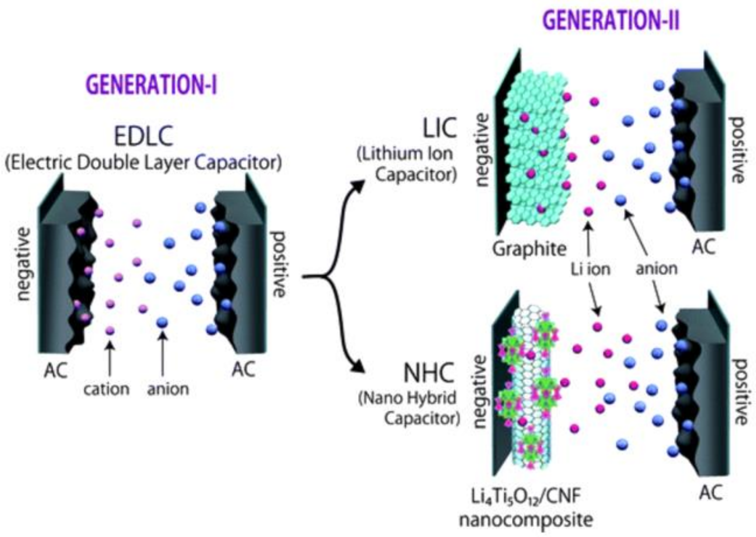


Figure 8: Reconfiguration of Generation-I AC based EDLC system into Generation-II asymmetrical LIC and NHC Battery Systems (16).

Materials such as graphite, Lithium Titanate (LTO) and Titanium Dioxide (TiO_2) are widely used in LIBs, however, these materials fall short of LICs requirements (59), (62). This is mainly due to their sluggish Faradaic bulk reaction leads to low power density. In addition, their high specific capacity cannot be fully utilised in LICs as a result of imbalance of charge and discharge rates between EDLCs type electrodes and battery type of electrodes (16), (59). Furthermore, noncarbon materials have relatively poor electrical conductivity would result in high voltage drop and causes high charge and discharge overpotential (59). As a result, Hard Carbon (HC) is also investigated as one of the favourable anode materials due to its relatively cheap cost, ease to synthesise and excellent performance in LICs. The disordered microstructure composed of cross-linked carbon layers is believed to be the main factor of simplistic intercalation reaction between the Li-ions and the electrodes, and hence, higher energy density and better charge and discharge rate without losing its cyclic stability (16), (59).

Since the discovery of graphene in 2004, this two-dimensional (2D) materials with an ultrathin layered structure and infinite planar length have attracted the attentions in many applications, especially energy storage (15). Graphene is a basic building block of graphitic materials, and is a planar honeycomb lattice, which consists of a hexagonal carbon ring made up of SP^2-bonded carbon atoms. It has high theoretical surface area and a porous structure, excellent electrical conductivity, high chemical and thermal stability, and high mechanical strength, which make it one of the favourable materials in energy storage devices (12), (63). However, it is important to acknowledge these excellent properties are based on its nanoscale structure; a bulk graphene can suffer from aggregation and over-stacking, and hence hinder the chemical reactions (63). Moreover, graphene is not readily used as the basis of electrochemical sensors due to its high cost and lack of manufacturing scalability (64). In addition, owing to the higher redox potential of the metal oxides, the energy densities of LICs are restricted to below 90Wh/kg, which is insufficient for practical use. Prelithiated graphite or prelithiated hard carbon is considered as the only option to achieve an energy density higher than 150Wh/kg (65). Thus, hybrid anode materials are introduced as innovative strategies to improve the performances of LICs. Different hybrid electrodes are prepared as graphene-based nanocomposites, carbon coating, and incorporation of carbon nanopipes. Materials such as carbon-coated LTO (C-LTO), graphene-based LTO (G-LTO), reduced graphene oxide (rGO), flash-reduced graphene oxide (FRGO), partially reduced graphene oxide (PRGO) have all yielded exceptional results in improving the energy density and performance of the LICs (12), (13), (15), (61), (63), (66). Table 2 below has summarised the performances of LICs with different combinations of materials for anode and cathode from various studies.

Anode	Cathode	Energy Density (Wh/kg)	Power Density (W/kg)	Cycling Stability	Ref.
N-doped Carbon Nanopipes	rGO	262 at 450W/kg	9000W/kg at 78Wh/kg	91% after 4000 cycles	(66)
TiO_2	AC	85 at 1000W/kg	20,000 at 44.4 Wh/kg	78.5% after 10000 cycles	(67)
Fe_2O_3-C	Nitrogen-doped hierarchical porous carbon (N-HPC)	65 at 368W/kg	9000 at 31Wh/kg	84.1% after 1000 cycles	(68)
MoS_2-graphene	AC	188 at 200Wh/kg	40000 at 45.3Wh/kg	80% after 10000 cycles	(69)
Niobium nitride	AC	149 at 200Wh/kg	45000 at 5Wh/kg	95% after 15000 cycles	(70)
Lithiated single walled CNT and graphene composite	SWCNT/SG	222 at 415W/kg	3800 at 58Wh/kg	58% after 5000 cycles	(71)
MnO/C	Biomass-kapok fiber derived AC	100 at 83W/kg	200,000 at 30 Wh/kg	70% after 5000 cycles	(72)
MnO cubes	AC	227 at 57W/kg	3000 at 9Wh/kg	92.5% after 3500 cycles	(73)
$MnFe_2O_4$-C	3D amorphous carbon	157 at 200W/kg	10000 at 59Wh/kg	86.5% after 6000 cycles	(74)

Table 2: Summary of LIC energy and power densities with different electrodes combinations

Table 2 has shown that the energy and power densities of LICs can be improved by utilising advanced materials such as carbon nanopipes, graphene and rGO. In particular, rGO is gaining more popularity as electrodes materials due to its similar properties as graphene and its relatively lower cost and ease to manufacture in industrial viable scale compared to graphene (64), (75). The commercially available LICs have the energy density of approximately 14Wh/kg at the power density of around 3200W/kg (76). In the most recent development, the LICs with Nitrogen-doped Carbon Nanopipes (N-CNPipes) as the anodes and rGo as the cathodes have successfully achieved energy and power densities of 262 Wh/kg at 450W/kg and 78Wh/kg at 9000W/kg. This breakthrough has proven that LICs can possess higher energy density than LIBs, which can be used as alternative power source for BEL and advanced EVs in the future (66).

Currently, the LICs on the market are mostly made from AC in the form of coin cell or AA battery due to its low cost and high specific surface area (76). Ultimately, AC derived from agricultural by-products and biowastes is becoming more popular because of the recycling and the rise of awareness. Biowastes materials such as banana peels, rice husks, orange peels, alginate seaweed, coconut shells and sugar cane bagasse have been used to obtain ACs that have been effectively tuned for supercapacitor applications with optimum parameters (62), (65), (77).

3 Size and Design of Battery System for BEL

3.1 BEL Performance Requirements

To calculate the minimum energy required by a BEL, the minimum acceptable vehicle performance requirements were defined. Considering the requirements to comply with modern traffic and the regulations, assumptions and minimum requirements were defined as below:

- The lorries, goods vehicles are classed into 3 different class based on the guide from Department for Transport (DfT) and vehicle weights.
- Lorries that are weighted below or equal 7.5tonnes are considered as LGVs, Lorries that are weighted from 7.5tonnes to 15tonnes are considered as Medium-Freight Vehicles (MFVs), lorries that are weighted over 15tonnes are considered as HGVs (24), (78).
- The maximum speed of LGVs are expected to be 112km/s and the maximum speed for MFVs and HGVs are expected to be 96km/hr due to the speed limits and regulations in the UK (79).
- The acceleration of the vehicles is assumed to be 1.341m/s^2 (97km/hr in 20seconds) similar as Tesla semi-trailer (50).
- The vehicles are expected to have the range of 495km because EU regulation 561/2006 requires every truck driver to have the compulsory 45 minutes of rest period after 4.5hours of driving (80).

3.2 Energy Consumption

The vehicle parameters were selected based on the values from the BELs on the market. The parameters are summarised as Table 3 below:

Parameter	Default Value
Maximum weight of the vehicles	LGVs = 3.5tonnes MFVs = 15tonnes HGVs = 44tonnes
Drag Force Coefficient (C_d)	LGVs = 0.5 (81) MFVs = 0.63 (32) HGVs = 0.63 (32), (49)
Tyre Size	LGVs = 185R 14C MFVs = 315/80R 22.5 HGVs = 385/65R 22.5 (82), (83)
Tyre Pressure	LGVs = 8.5bar MFVs = 9bar HGVs = 9bar (82)
Dimensions	LGVs = 6.44×2×2.692 MFVs = 8.1×2.55×3.6 HGVs=18.75×2.55×4.65 (84)
System Efficiency	90% (36), (45)
Range of the vehicle	495km
Air Density	1.225 kg/m^3
Road Slope Angle	0^o
Energy Density of LICs	262Wh/kg (66)
Power Density of LICs	450W/kg (66)
Minimum battery state-of-charge (SOC)	20% (56), (85)

Table 3: Defined Parameters for BELs Energy Consumptions Calculations

The energy consumption is calculated based on the road loads. The total force required to move the vehicle is the sum of Rolling Resistance Force (F_R) and Aerodynamic Drag Force (F_A).

$$F_T = F_I + F_R$$

The equation of Rolling Resistance Force:

$$F_R = C_R . W$$

Where C_R is the coefficient of rolling resistance between the tyre and the road;

W is the weight of vehicle (N).

The equation for the coefficient of rolling resistance between the tyres and road:

$$C_R = 0.005 + \frac{1}{P}\left(0.01 + 0.0095\left(\frac{V}{100}\right)^2\right)$$

Where P is the tyre pressure (bar);

V is the velocity of the vehicle (km/hr)

The equation of aerodynamic drag force:

$$F_A = \frac{A}{2}(C_d)\rho V^2$$

Where A is the frontal area of the vehicle (m^2);

C_d is the drag coefficient of the vehicle;

ρ is the air density (kg/m^3);

V is the velocity of the air (m/s)

Using calculated total force required to move the vehicle, the expected energy consumptions of the vehicles can be determined.

The equation for energy required:

$$E_T = F_T \times D$$

Where D is the range of the vehicles

To determine the total power required for electric lorries with designated range, the power equation is used.

Equation of Energy Consumptions (Wh):

$$Energy\ Consumption = \frac{E_T}{t}$$

Where E_T is the total energy consumption (J);

t is the time (s)

From here, the capacity of energy storage can be determined. The minimum SOC of the battery is assumed to be 20%, as total discharge of the battery would result in shorter lifecycle and damaging the electrodes (85).

Furthermore, the power equation is used to calculate the power capacity required for the vehicles:

The equation of Power:

$$P_T = F_T \times V$$

Where F_T is the total force required to move the vehicle (N);

V is the velocity of the vehicle (m/s)

The results are summarised as Table 4 below:

Vehicle Type	Total Force (N)	Energy Required (MJ)	Power Required (kW)	Energy Consumption (kWh/km)	Total Energy Consumption (kWh)
LGV	1800	890	55	0.51	290
MFV	4600	2360	127	1.15	570
HGV	6720	3330	187	1.70	840

Table 4: Summary of Energy Consumptions of Goods Vehicles

The results calculated are used to compare the actual values from selected BELs that are commercially available for purchase. The criteria of these selections are as following:

- The vehicles must be fully powered by battery or any other electrochemical energy storages.
- Hybrid vehicles will not be considered as the systems and operating conditions are not similar with BELs.
- Selected BELs must be or will be commercially available on the market in the next two years (2021) with reliable and valid datasheets provided by the manufacturers.

Table 5 has summarised the specifications of commercial BELs that meet the criteria for the selections. The range of the lorries may be varied due to their different purposes in road freight transportations and delivery areas. However, most of the manufacturers aim to provide a range of at least 300km as lorries can cover approximately 350km during the 4.5hours of driving period before the compulsory rest period based on the EU regulation 561/2006 (9), (80).

Vehicle Type	Manufacturer	Range (km)	Battery Capacity (kWh)	Energy Consumption (kWh)	Energy Consumption (kWh/km)
LGV	Mitsubishi	120	82.8	82.8	0.69
	Navistar	161	80	80	0.50
MFV	Renault	300	200-300	300	1.00
	Volvo	100-300	100-300	300	1.00
HGV	Tesla	480-800	N/A	600-1000	1.25
	BYD	200	350	350	1.75
	Freighliner	400	550	552	1.38

Table 5: Specifications of BELs (9)

In comparison to the specifications of BELs, the calculated values are considered within acceptable range of the data provided by the manufacturers. The calculated energy consumption of LGVs is only 2% different to that of Navistar LGV whereas 26% different to Mitsubishi's LGVs. However, this has proven the calculation method is accurate and appropriate as the calculations for the energy consumptions of LGVs are based on the specifications of Navistar E-Star LGV such as the dimensions of the vehicle and the drag force coefficient. Both manufacturers of MFV, Volvo and Renault have developed their BEL with similar energy consumptions, however their energy consumption is 15% lower than estimated energy consumption. In term of HGV, the energy consumption of BEHGV is calculated to be 1.70kWh/km which is within the range of selected HGVs' energy consumptions from 1.25kWh/km to 1.75kWh/km. This is mainly due to the differences in vehicle designs, type of battery employed on the vehicles and the designated range for the vehicles. Tesla claimed their advanced vehicle design will allow their BEHGVs to have significantly lower drag coefficient (0.36) in comparison to other manufacturers (50). Additionally, this value is lower than projected value of drag coefficient of 0.45 for the vehicles in the future (49). Tesla's vehicle design with extreme low drag coefficient would greatly improve the energy efficiency and the energy consumptions of the vehicles, and ultimately the battery size required on the vehicles. Subsequently, this may prove as the source of high percentage difference of 36%, which is the highest inaccuracy in this comparison. The energy consumption of BYD's HGV is 3% different to calculated value, however BYD is the only manufacturer that employs Lithium Iron-Phosphate (LFP) battery as the power source for the HGVs.

Vehicle Type	Manufacturer	Energy Consumption (kWh/km)	Estimated Energy Consumption (kWh/km)	Percentage Difference (%)
LGV	Mitsubishi	0.69	0.51	26%
	Navistar	0.50		2%
MFV	Renault	1.00	1.15	15%
	Volvo	1.00		
HGV	Tesla	<1.25	1.70	36%
	BYD	1.75		3%
	Freighliner	1.38		23%

Table 6: Percentage differences of calculated energy consumptions with literature values

In addition, BYD's vehicle is designed with the range of 200km which is half of the range of the BEHGVs from Tesla and Freightliner (9), (86). Moreover, the maximum weights that can be carried by the HGVs from BYD (36t) and Freightliner (40t) are significantly lower than assumed weight of BEL in this study (44t). Hence, it is apparent that these manufacturers only need to employ smaller capacity of batteries for their BEHGVs.

3.3 The Power Required for Acceleration

To calculate the powers required for the accelerations of the vehicles, the Inertial Force (F_I) required to move the vehicle must be calculated.

Equation of Inertial Force:

$$F_I = m \times a$$

Where m is the mass of the vehicle (kg);

a is the acceleration rate of the vehicle (m/s^2)

The acceleration of the vehicle is set to 0-60 mph (approximately 0-97kph) in 20 seconds which is similar as Tesla Semi-trailer (50).

Once Inertial Force is calculated, the output torque can be calculated by using torque equation.

Equation of Output Torque:

$$\tau = F_I \times r_T$$

Where r_T is the radius of tyre

The estimated peak power demands of the vehicles can be calculated using power equation.

Equation of Peak Power Demand:

$$P_P = F_I \times V$$

Where F_I is the inertial force;

V is the velocity of the vehicles (m/s)

Using the power density of LICs, the weight of LICs required for the acceleration of the vehicles can be determined.

$$Weight\ of\ LIC = \frac{Peak\ Power\ Demand}{Power\ Density\ of\ LIC}$$

The results are summarised as Table 7 below.

Type of Vehicle	Inertia Force (N)	Torque (Nm)	Peak Power Demand (kW)	Weight of LIC (tonne)
LGV	10058.33	3576.74	307.34	0.68
MFV	20116.67	11496.68	614.68	1.37
HGV	59008.89	33723.58	1803.05	4.01

Table 7: Peak Power Demands of the vehicles and the weight of LIC required

Based on the results, the minimum LIC weights required for the LGVs, MFVs and HGVs are 0.68, 1.37 and 4.01tonnes respectively in order to provide sufficient power for desired acceleration rate of 0-97kph in 20 seconds (1.34m/s^2).

3.4 Weights and Capacities of LICs

The efficiency of electric motor is approximately 90%, which is significantly higher than ICEs (36), (45). Furthermore, the minimum SOC of the battery is set to 20%, as 80% depth of discharge (DOD) should be able to avoid damaging the battery and subsequently shorten the battery lifecycle and energy capacity (56), (85), (87).

From Table 4, the energy consumptions of the vehicle are determined and known. Consider the efficiency of the electric motor and the DOD of the battery, the capacities of the LICs for the BELs are calculated.

$$Capacity\ of\ LIC = \frac{E_T}{\eta_E . DOD}$$

Where E_T is the energy consumption;

η_E is the efficiency of electric motor;

DOD is the depth of discharge of LIC

From this, the weights of the LICs are determined, using the energy density of the LICs.

$$Weight\ of\ LIC = \frac{Capacity\ of LIC}{Energy\ Density\ of\ LIC}$$

The results are summarised as Table 8 below.

Table 8 has shown the estimated weights of LICs on LGV, MFV and HGV are 1.53, 2.45 and 4.45 tonnes respectively. The estimated weights are higher than the minimum weight required in Table 7, which represents the high-power density of LICs can provide sufficient power for desired vehicle acceleration rate of 1.34m/s^2 with designated travel range of 495km. Based on the results, a LIC with the capacity of 1200kWh is needed for the HGV to travel approximately 500km with the maximum weight of 44t. This estimation is similar with the study from Sripad and Vismanathan (49).

Type of Vehicles	Energy Consumptions (kWh)	Capacity of LIC (kWh)	Weight of LIC (tonne)
LGV	290	400	1.53
MFV	570	790	2.45
HGV	840	1200	4.45

Table 8: The capacities and the weights of the batteries

In comparison to other manufacturers, most of BEHGVs are restricted to short distance for urban delivery due to low energy density of the battery which results in heavy weight vehicle battery. These battery masses have significant influences on the payload of the vehicles, which is utterly most important factor in road freight transportation. Consequently, the manufacturers would shorten the range of the BELs in exchange of higher payload of the vehicles. Though Freightliner and BYD have developed their own BEHGVs, which are available on the market, the weights of the batteries to power the vehicles are not known. Furthermore, Tesla have yet to provide a full specification for their Tesla Semi BEHGV. Hence, it is impossible to compare the weights of the battery and its payload capacity. However, based on a rough comparison, the battery cells of Tesla Semi can weight up to 2.8t for 480km version and 6.4t for 800km version (9). The BELs would typically have four electric AC induction motors, inverter electronics and transmission, which could weight approximately 400kg (9), (43). However, BYD T9SJ BELs have only two electric motors due to its shorter range (200km) and lower GVW in comparison to Freightliner eCascadia and Tesla Semi. The mass of the battery required may seem relatively high and may result in lower payload of the vehicle. However, it is important to take into account that the heavy ICE, the fuel system and the exhaust hardware will be replaced by much lighter electric motor system. It is estimated that the weight of ICE, fuel tank and exhaust system can be as heavy as 3t (9), (43).

3.5 The Volumes of LICs

The volume of a battery is less critical than the weight as some volume can be installed under the chassis and the volume required to store a battery is relatively lower than the required additional mass for the battery. The current energy density of the battery as compared to the required volume is estimated to be 40% higher than the energy density in term of unit mass. With this estimation, the volume required is estimated. In this study, the energy density of LIC is assumed to be 262Wh/kg, hence the energy density of LIC in term of volume would be approximately 366.8Wh/l. Table 9 has summarised the volume of LICs required for different type of goods vehicles. The volumes of LIC battery system are for LGV, MFV and HGV are estimated to be 1.09m^3, 2.15m^3 and 3.27m^3 respectively. It is difficult to determine the exact dimensions of the battery pack as it involves complicated battery chemistry in pack density, arrangement of the battery cells in pack and architecture of battery pack (25). However, it must be taken the account of the regulations for the dimensions in the country and the impact of the change on the vehicle dimensions (84). Evidently, the increasing length of the vehicle would result in increment of aerodynamic drag force due to the rise of aerodynamic drag coefficient of the vehicle (32), (88).

Type of Vehicles	Energy Consumptions (kWh)	Capacity of LIC (kWh)	Volume of LIC (litre)	Volume of LIC (m^3)
LGV	290	400	1091	1.09
MFV	570	790	2154	2.15
HGV	840	1200	3272	3.27

Table 9:The Volume of LICs Required

Hence, most of the battery packs for the goods vehicles are designed to be installed under the chassis to avoid additional aerodynamic drag force for the vehicle by maintaining its streamlined vehicle design (32), (43). Figure 9 has shown how the battery pack can be installed under the chassis of the BELs. Balqon's Nautilus XE20 carries a 140kWh of LIB pack which supports a 150kW electric motor with minimum speed of 40km/hr.

Figure 9: The Battery Pack of Balqon's Nautilus XE20 (43).

Similarly, the battery pack of Freightliner eCascadia is installed under the chassis as shown in Figure 10. Such design has been proven to be less technical challenging and to have less impact to the overall performances of the vehicles (89).

Figure 10: Freightliner eCascadia Electric Chassis (90).

3.6 Chapter Summary

This chapter defined the assumptions and parameters for the calculations. This chapter also presented the main findings from the calculations on the energy consumptions of goods vehicles to travel for 4.5hours or 495km, and the power required for the goods vehicles to accelerate in designated rate. The estimated energy consumptions were then used for comparison with existing BELs on the market. The comparison has shown that the estimations are slightly higher than the actual values with the percentage difference up to 36%. However, it is noticeable that the result of energy consumption estimation for HGV (1.70kWh/km) is within the range of actual values from other manufacturers such as Tesla, BYD and Freightliner, which ranged from 1.25kWh/km to 1.75kWh/km. The percentage difference for HGV energy consumption is ranged from 3% to 36%. This is mainly due to the significant influences of the vehicle designs with the parameters such as the drag force coefficient, the size of the tyres and the maximum weights of the vehicle on the vehicle energy consumptions. The lower the drag force coefficient, the lower the energy consumptions of the vehicle which can ultimately result in lower battery capacity required and lower battery weight. In addition, some information such as battery weight, energy density of the battery and drag force coefficient of the vehicles remain undisclosed, which made the estimations and the validity of the data remain uncertain and speculative.

The results of peak power demand calculation indicated the minimum masses of LICs required for LGV, MFV and HGV are 0.68t, 1.37t and 4.01t respectively in order to achieve the desired acceleration rate of $1.34 m/s^2$. The LIC capacities were then calculated by taking account of motor efficiency and DOD. It is not possible to verify the accuracy of the battery capacities as the actual values are influenced by vehicle range, acceleration rate and maximum weight of the vehicle. These parameters vary with the manufacturers and the vehicle design, and some parameters are undisclosed. The weights of LICs required for the vehicles to travel with designated range at desired speed were then calculated. The masses required of LICs for LGV, MFV and HGV are 1.53t, 2.45t and 4.45t. The calculated masses are higher than the estimated minimum LIC masses to achieve the desired acceleration rate, which prove the masses of LICs for the vehicles are able to sustain the operations of road freight transportations in desired conditions.

The results were then compared to the estimations from other studies (9), (43), (49). This chapter also discussed the importance of the battery masses in terms of payload and GVW, and how the vehicle power system is changed and transform ICE system to electric motor system. Such transformation may allow possible feasibility of employing LICs on goods vehicles.

However, it is important to take into account that the estimations are roughly agreed, and the results of the analysis displayed subtle differences that cannot be verified by actual values. This limitation may raise speculations and questions on the reliability and credibility of this analysis.

On the next chapter, the significances of vehicle design variables such as the coefficient of rolling resistance and the drag force coefficient, and the energy density of the battery on the results will be analysed and discussed. In addition, the charging infrastructures and potential alternative charging technologies are also evaluated and discussed. Subsequently, the next chapter will also provide evaluation on the results and the challenges must be overcome for the project to be realised.

4 Discussion

4.1 Effect of Vehicle Parameters on Vehicle Energy Consumption

4.1.1 Lightweight Material

The design of vehicle can have a significant impact on its energy consumption. The parameters of EVs and BELs are often better optimised than conventional ICE vehicles due to technological restrictions on the battery capacity and battery weight. Hence, advanced materials such as carbon fibre and polymer composites (87), (91). It is estimated the replacement of heavy steel components with materials such as high-strength steel, aluminium or polymer composites can decrease the component weight by 10% to 60%. While advanced materials such as magnesium and carbon fibre reinforced composites are estimated to reduce the vehicle weight by 50-75% (91). In addition, the use of lightweight materials for vehicle structure can improve the vehicle durability, vehicle dynamics and flexibility of vehicle structural design (92), (93). However, in case of goods vehicle and road freight transports, the lightweight materials will not reduce the overall weight of the vehicle, however it will increase the payload of the vehicle and consequently improving transportation efficiency. In addition, the weight reduction from the lightweight material can compensate the weight loss for the battery (94).

4.1.2 Aerodynamic Drag Coefficient

Other than the use of lightweight materials, the manufacturers are focusing minimising the aerodynamic drag coefficients of the vehicles by introducing more streamlined vehicle design. Goods vehicles are widely believed aerodynamically inefficient in comparison to other land vehicles (32). It is estimated approximately 52% of the total fuel consumptions of goods vehicle to travel at 100km/h are used to overcome the aerodynamic drag (32), (88). Add-on features such as roof deflectors, aerodynamic trailers, roof fairings and trailer side panels are made available to be retrofitted to existing vehicles to improve their aerodynamics (1). With combinations of aerodynamics fairings in different parts of the vehicle body can reduce the aerodynamic drag force by up to 26% (32). Currently, most of the HGVs have an average drag force coefficient of 0.63, with a projected value of 0.45 for future vehicles (49). As aforementioned, this study assumed the drag force coefficient of BELs would be 0.5 for LGV, and 0.63 for MFV and HGV. However, in the recent reveal, Tesla claimed their BEHGV, Tesla Semi has the drag force coefficient of 0.36 which is significantly lower than projected value for the future vehicles (50). The drag force coefficient of Freightliner eCascadia is not revealed, however Daimler claimed its eCascadia is more fuel efficient by 115% than a comparison HGV from 2009 (95). Figure 11 below has shown the relationship of aerodynamic drag coefficient and vehicle energy consumptions. The direct proportional relationship has indicated similar conclusion as the study from Sweeting et al. (87).

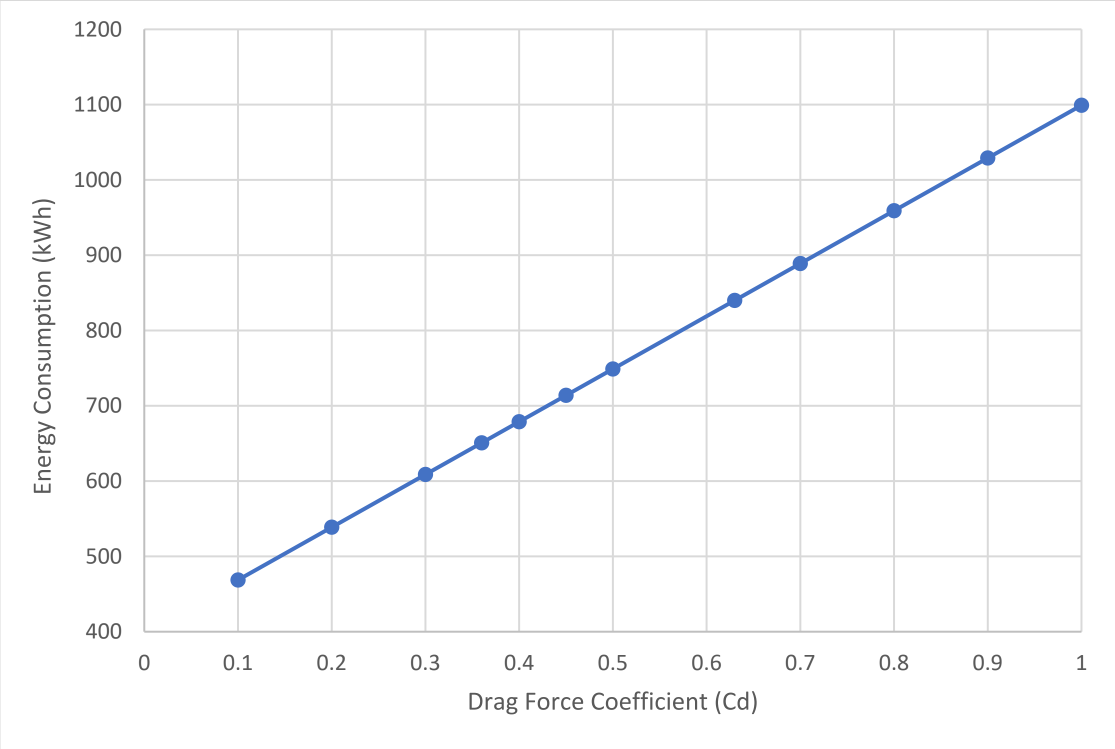


Figure 11: Effect of Drag Force Coefficient Variations on Vehicle Energy Consumptions

Based on the projected value of drag force coefficient, 0.45 drag force coefficient would reduce the energy consumption of HGV by 14.8%, from estimated 840kWh to 714kWh. This would offer a significant reduction of 15.1% on the mass of LIC required on the HGV from 4.45t to 3.78t. However, based on the design of Tesla Semi, which has lower drag force coefficient of 0.36, the energy consumption of vehicle would effectively drop by 22.5% to 651kWh. This would reduce the mass of LIC to 3.45t. Such improvement on the coefficient of aerodynamic drag force can greatly improve the feasibility of using LIC as power source of BEL by lowering the battery cost and without sacrificing the payload capacity.

4.1.3 Rolling Resistance

Furthermore, low rolling resistance tyre is being developed as the rolling resistance of the tyre has continued to contribute 20 to 30% of the total vehicle fuel consumption. (96). It is widely believed that the rolling resistance coefficient is independent of the load. However, this statement may not be true as most of the energy dissipation in running tyre is due to the hysteretic losses that are dependent on tyre deflection thus on payload and inflation pressure (97). In case of goods vehicles, improving the rolling-resistance can be significant in reducing energy consumption of the vehicle. A reduction of 10% on rolling resistance can save the heavy vehicles up to 3% of fuel consumption (96). Higher payload and vehicle weight would require higher inflation pressure in order to ascertain proper interface between the tyres and the road surface. When the vehicle is moving, the tyre temperature would increase due to the traction force and the heat generated from the rolling resistance. As a result, the inflation pressure increases and causes suboptimal interface between the tyres and the road surface. Consequently, the rolling resistance increases and results in lower fuel efficiency of the vehicles (96), (97). It is estimated an increase of 5kPa to 20kPa on the inflation pressure would occur after long period of rolling for the tyres at the speed of 80km/h (97).

In this study, the rolling resistance coefficient of LGV is determined to be 0.00753, and 0.00739 for MFV and HGV due to higher tyre pressure and tyre radius. However, the mean rolling resistance coefficient of goods vehicle tyre is estimated to be around 0.0063 and projected value for future vehicles would be around 0.0045 (49). The rolling resistance of the tyre can be minimised by introducing new material composites to the tyre or by implanting plugs into the tread. The incorporation of silica into the tyre design can reduce the rolling resistance without losing the grip (1), (31). In addition, the implantation of the plugs into the tread can offer more stiffness to the tread perpendicularly and reducing the tread vertical deformation during the loading and unloading scenario. Hence, this implementation would reduce the rolling resistance without causing significant effect on other features of the tyre (96). However, rolling resistance can be an important factor for the safe operation of the vehicle. The rolling resistance of the tyre would allow certain levels of grip to ensure the controllability of the vehicle and to avoid the vehicle to slip especially during the rain (31).

As previously mentioned, the rolling resistance coefficients are calculated to be 0.00753 for LGV and 0.00739 for MFV and HGV based on the tyre pressure. However, the mean rolling resistance coefficient for goods vehicle is estimated to be approximately 0.0063 and it is projected that the rolling resistance coefficient will drop to 0.0045 for future vehicles (49). The differences in this variable can have significant influence on the energy consumptions of the vehicles and ultimately the masses of the LICs on the vehicles. Figure 12 below has indicated a direct proportional relationship between the rolling resistance coefficient and the energy consumption of the vehicle. Similar outcome was observed in the study by Sweeting et al. (87).

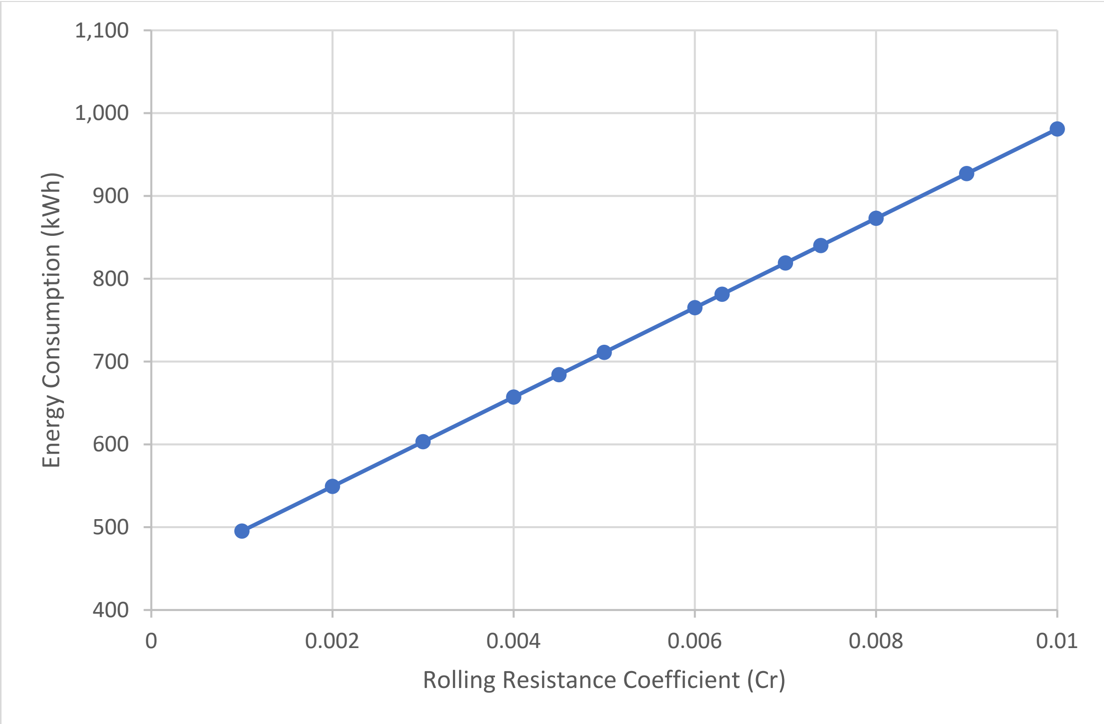


Figure 12: Effect of Rolling Resistance Coefficient Variations on Vehicle Energy Consumptions

Based on the mean rolling resistance coefficient of 0.0063, the energy consumption of the vehicle will be lowered by approximately 7%, from 840.04kWh to 781.23kWh, and ultimately the battery weight will be lowered by approximately 6.97%, from 4.45t to 4.14t. However, on the basis of projected value for the rolling resistance coefficient of future vehicles, the energy consumption of goods vehicle would be decreased by 19.55% to 684.11kWh, and the battery weight can drop by 18.56% to 3.63t.

4.1.4 Energy Density

In this study, the energy density of LIC used for calculations is 262Wh/kg, which is based on the experiment conducted by Dubal and Gomez-Romero (66). However, the current energy density of LIC on the market is only 10Wh/kg (76). Such low energy density would obsolete any possibility of using LIC as main power source in BELs as the mass and the volume of the battery would increase from minimum 1.53t for LGV to 40t in order to travel for 495km or 4.5hours. However, with the recent breakthrough from the experiment by Dubal and Gomez-Romero, they have successfully reported one of the highest energy and power densities for LICs energy storage (66). Li-ion system is expected to have potential to reach 350Wh/kg, other battery systems such as Lithium-Sulphur (Li-S) and Lithium-air (Li-air) have the theoretical energy densities of 350Wh/kg and 13,000Wh/kg (43), (49). However, both battery systems have yet to be commercialised and both technologies are relatively undeveloped and remaining as speculations. Li-air technology will not be considered in this study due to the large uncertainties on its electrochemical properties and complicated battery chemistry (43).

Table 10 has summarised the weights required for the different types of battery systems as the power source of BELs. It can be observed that improvements on the energy density of the battery would greatly reduce the mass of the battery system and hence increases the payload of goods vehicles and the range of the vehicles. However, in comparison to conventional ICE lorries, the BEL technology still faces ginormous challenge of improving the practical energy density of the battery. The energy density of diesel is approximately 40times higher than that of batteries. Though the electric powertrains are more energy efficient than ICEs, the energy density of the batteries is still required to be improved by at least a factor of 3 to achieve the same range as ICE vehicles (43).

Vehicle Type	LIB (tonnes)	LIC (tonnes)	Li-S (tonnes)
LGV	1.60	1.53	1.14
MFV	3.17	2.45	2.26
HGV	4.67	4.45	3.33

Table 10: The Weights Required for Various Types of Battery System on BELs

4.1.5 Electric Motors

In comparison to the industrial applications of motors, the electric motors in EVs usually require frequent start-and-stop operation, higher rates of acceleration or deceleration, higher torque for low-speed hill climbing or lower torque for high-speed cruising, and hence wider speed range of operation (98), (99). Brushless DC motor is a popular candidate for small EVs as it can improve the energy efficiency by 10 to 20%. This is mainly due to improved efficiencies and reduced sizes in comparison to Mechanical Commutator (MC) motors, Induction Motors (IMs) and Permanent Magnet Synchronous Motor (PMSM) (87), (99). In addition, Brushless DC motor are becoming more popular, as high reliability and maintenance-free operation are prime considerations for electric propulsion (99). However, it is evident that cage IMs and PM motors are more dominant in the market as they are cheaper, better suited to larger and more powerful vehicles (87). Compared with DC motors, AC IMs have the advantages such as lightweight nature, small volume, low cost, and high efficiency. These advantages are prime considerations for the design of EVs, HEVs and BELs, where mass and volume are one of the constraint factors (98). Hence, AC IMs are used in several EVs such as General Motors EV1, Tesla Roadster, Model S and Model X, BYD T9 and Freightliners eCascadia (86), (100), (101), (102).

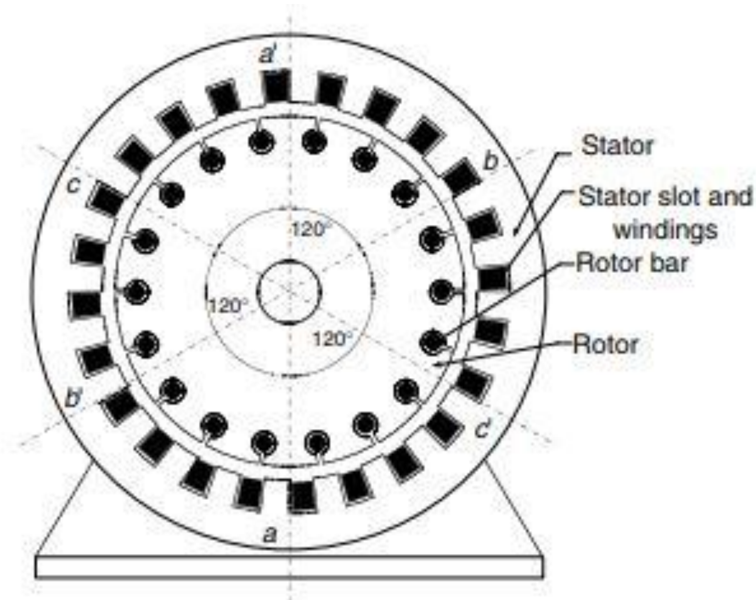
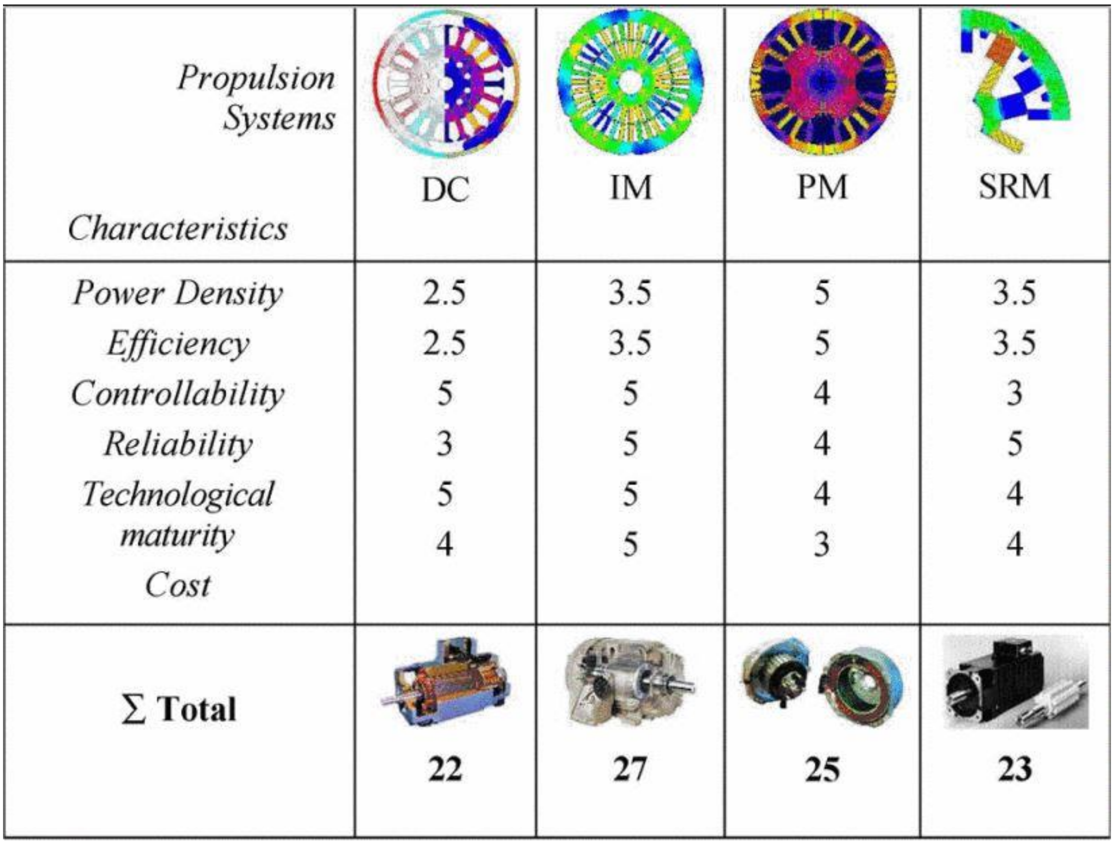


Figure 13: Cross-section of Induction Motor (98)

IMs can be classed into two different types, wound-rotor and cage motor. Cage IMs are widely accepted due to their reliability, ruggedness, sturdiness, low maintenance and ability to operate in hostile environments (98), (100). However, IMs face a number of drawbacks, such as high loss, low efficiency, low power factor, and low inverter-usage factor. Consequently, to improve the efficiency of IMs, a series of innovative control techniques has been implemented. The introduction of multiphase pole-changing IM would solve the issue of breakdown torque in the motor by allowing extension of constant-power region without oversizing the motor (100).

PMSMs, also known as Permanent Magnet Brushless Motors (PMBMs) are the most capable of competing with IMs for the electric propulsion of HEVs and EVs. This is mainly due to its high power density (significant lower volume and weight for a given output power), high efficiency, ease of cooling, low maintenance, low noise emissions and high reliability (98), (99). The use of high-energy density magnets would allow PMSMs to achieve high flux densities, which can consequently allow smaller and lighter motors in the vehicles (98). In addition, the lack of current circulation in the rotor results in efficient heat dissipation to the surroundings as the heat only produced from the stator. This would offer stability to the overall system due to ease of control, greater fault tolerance and better reliability to the motor operations and performances (98), (99), (100). However, PMSMs suffer a number of disadvantages that cause it less attractive in EV application. PMSMs require rare-earth magnets to be functional, however such materials are more expensive than other magnets, which can introduce additional cost to already expensive EVs. In addition, PMSMs have limited constant power range, which is crucial in achieving high vehicle efficiencies. The design of PMSMs is not capable of achieving a maximum speed of twice the base speed (98). Furthermore, the performance of PMs may drop during the extreme high-speed operation due to demagnetisation of the magnets (98), (100). This is mainly due to high opposing magnetomotive forces and high temperatures. Due to the compact requirement of the motor in EVs, maintenances are often required to ensure the operability of the magnet (98).

Switched Reluctance Motors (SRMs) is a synchronous machine operating from inverter-driven square wave unipolar currents as torque is created by rotor saliency and pulsed currents. These motors do not require permanent magnet or winding on their rotor and hence offer fault tolerance, reliability and low maintenance cost (98), (99), (100). In addition, SRMs are able to operate in extreme long constant-power range that allows it to operate in high-speed operation without facing the concern of mechanical failures due to high level centrifugal force (98), (100). With the soaring cost of rare earth magnets, the interest in the use of SRM for EV applications has increased and hence the advancement of SRM technology. Ultimately, Nidec introduced their first SRM for EV application in 2012, which is claimed to have similar performance as IPM machine with relatively low cost (100). However, SRM exhibits several disadvantages that can be critical for HEV and EV application, such as acoustic noise generation, torque ripple, excessive bus current ripple and electromagnetic-interference noise generation (99). Moreover, SRM requires complicated controllability due to the nonlinearity of its magnetic circuit. Its control is heavily depending on the mechanical and electrical parameters, such as air gap, resistance, motor stack length and slot height. These parameters are not possible to be controlled in mass production and real-world operation (98), (103). These parameters variations can cause significant degradation of the drive performance due to uncorrelations in the control system as parameters such as air gap can change due to mechanical vibration wearing, and the resistance in windings and inductance would vary with the temperature (99).



Propulsion Systems / *Characteristics*	DC	IM	PM	SRM
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Σ Total	**22**	**27**	**25**	**23**

Table 11: Electric-Propulsion Systems Performance Evaluation (100).

Nevertheless, IM is still the most common electric motor for the electric propulsion of HEVs, EVs and BELs (98), (100). This is mainly due to its outstanding overall performances in comparison to other electric-propulsion systems, which can be observed from Table 11. Hence, it is reasonable to assume IMs will continue to lead as the top selection of electric propulsion systems for EV and BEL application in the future, which can be observed from latest introductions by manufacturers, such as Freightliner, Tesla and BYD. These manufacturers use 2 to 4 IM electric motors as the main electric propulsion for their BELs (50), (86), (102). In addition, aforementioned manufacturers use separated motors instead of one high power capacity electric motor for their BELs to increase the motor efficiency and to minimise the energy loss from transmissions, which ultimately would reduce the vehicle energy consumptions (99), (100).

4.2 Results Analysis

4.2.1 Battery Weights and Volume

As the calculations indicated, the weights of LICs required for LGV, MFV and HGV are 1.53t, 2.45t and 4.45t respectively. In comparison to conventional ICE vehicles, the weights of the fuel tank, exhaust systems and the heavy diesel engines are estimated to be 1t for LGV, 1.5t for MFV and 3t for HGV (9), (25), (43). This would represent the use of LIC battery system would inflict 4% or 0.53t of payload loss for LGV, 6.33% or 0.95t for MFV and 3.3% or 1.45t for HGV. Industry representatives argue that an increment of 2 to 4t would be too significant for BELs, however an increment of vehicle weight up to 2t is acceptable in road freight transport (43), (44). This has indicated the use of advanced LIC with high energy and power densities would allow advancement of BEL development in road freight transportations. In addition, the average load of HGVs by weight capacity in the UK is approximately 51% and 40.3% for LGVs (104). Hence, a slight decrease of payload capacity may not be as significant as fleet operators argued.

In addition, other vehicle variables such as aerodynamic drag coefficients, rolling resistance, average power draw by accessories and vehicle frontal area. These parameters are defined and assumed based on the available data from the vehicles with similar features, such as Navistar E-Star, Isuzu N-series, Tesla Semi and Freightliner eCascadia. As previously discussed, the industry has been introducing various advanced vehicle design or add-on features to minimise the energy consumption of the vehicles by introducing low rolling resistance tyres and by improving the aerodynamics of the vehicle. Figure 14 has demonstrated the relative impacts of the aerodynamic drag coefficient of the vehicle, coefficient of rolling resistance, vehicle frontal area and average power draw by accessories are very similar. A 50% variations on these variables would cause approximately 10% of loss or gain on the vehicle energy consumption. However, it is important to take account of the fact that the contributions from the coefficient of aerodynamic drag and vehicle frontal area are highly depending on vehicle speed. Therefore, the driving pattern and travel route may cause considerably variations with the driving cycle (1), (31), (87).

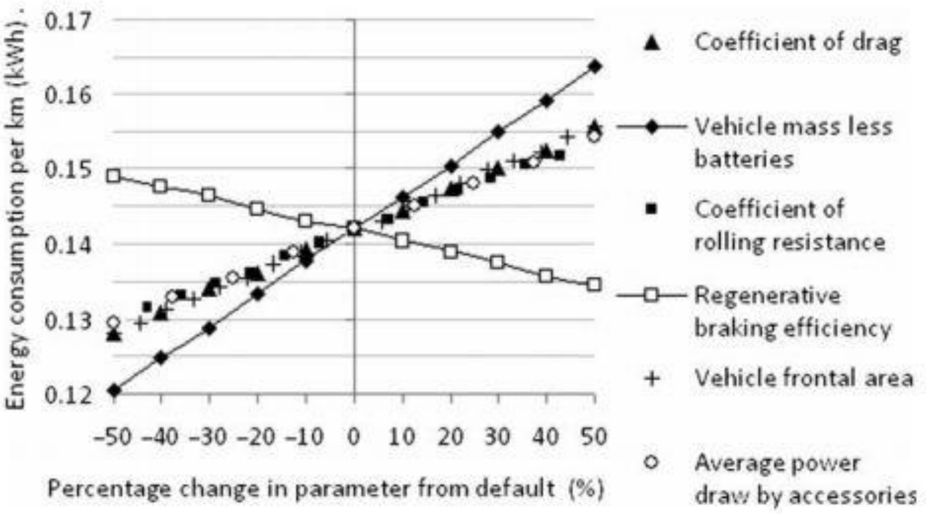


Figure 14: Effect of EV Parameters on Vehicle Energy Consumption (87)

In this study, these variables variations are investigated and analysed in previous section. Improvements on aerodynamic drag coefficient and the coefficient of the rolling resistance can greatly improve the energy efficiency up to 22.5%, and ultimately reduce the battery weight by 15.05%. The analysis has also included the comparisons with the actual, mean and projected values for the parameters such as aerodynamic drag and rolling resistance coefficients. Based on the projected values of aerodynamic drag and rolling resistance coefficients, the vehicle energy consumption can be further reduced by 33.57% from 840kWh to 558.02kWh and ultimately minimise the battery weight by 33.48% from 4.45t to 2.96t. This has indicated that the LIC battery system can be lighter than current ICE system and hence become the mainstream power source for the vehicles in the future.

On the other hand, battery volume is less crucial compared to the weight. This is mainly because some of the battery volume can be available under the chassis (43). However, it can still be a barrier as it may increase the length of the vehicle that may cause the aerodynamic drag coefficient to rise. As a result, vehicle energy consumption will increase and hence the battery weight (1), (30), (31), (32).

4.2.2 Analysis of Emissions Impacts

To address the questions on how BELs can contribute toward climate change goals and how much GHG emissions savings can be saved by electrification of goods vehicles, the analysis is narrowed down to one country, UK. This due to uncertainties in the implementations of the technologies and the complexity of road freight operations. Currently, it is estimated 121.4million tonnes of GHG were being emitted from transport sector in 2018 and approximately 31% of that is contributed by road freight sector (1), (104). Full electrification of goods vehicles in the UK would involve approximately 3.9million LGVs and 500thousand HGVs, and additional 2.16TWh of electricity demand on the grid (41).

Though the electrification of goods vehicles would significantly reduce the diesel consumptions from the vehicles, it would increase the demand of electricity in the UK by approximately 1%. Consequently, the GHG emissions from energy sector may increase and hence offset the carbon savings. Currently, the energy generated in the UK is 49.14% from natural gas, 40.4% from oil, 6.75% from coal and 3.24% from other energy sources such as solar, wind and nuclear power plant (104). And hence, it is assumed the same proportion of fuels to generate the electricity required to recharge the electrified goods vehicles. The estimated GHG emissions from electrification of goods vehicles is summarised as Table 12 below.

Fuel Type	Percentage (%)	Electricity Generated (TWh)	GHG Emissions (Mt)	GHG Emissions Induced by Travel Distance (Mt)
Natural Gas	49.14	1.06	0.191	2.865
Oil	40.40	0.87	0.235	3.525
Coal	6.75	0.15	0.048	0.720
Other Fuels	3.24	0.07	0.00	0.00

Table 12: Estimated GHG Emissions from Electrification of Goods Vehicles

The total GHG emissions from full electrification of goods vehicles is approximately 7.11million tonnes with the inclusion of the distance travelled by the vehicles to lift the goods. This would significantly reduce the GHG emissions from road freight sector by approximately 81.1%. However, it is important that this estimation does not include the goods vehicles travelled internationally between the UK and the EU. The decarbonisation of energy generation sector would further magnify the benefits and the GHG savings from the electrification of goods vehicles. Evidently, the increase of renewable energy generations capacity in the UK would further minimise the GHG emissions in energy sector induced by the introduction of BELs.

4.3 Charging Requirements and Its Impact on the Grid

4.3.1 Total Energy Demand

In this study, a LGV is estimated to consume approximately 0.4MWh of electricity, 0.64MWh for MFV and 1.2MWh for HGV, while the average annual electricity consumption of a household in EU is approximately 3.5MWh (25). Implying a single HGV charge would be equivalently charging one-third of the EU household in a year. In addition, fast charging of HGV would represent drawing as much power as 3000 to 4000 average UK houses. According to Dft, there were approximately 3.9million LGVs and 500thousand HGVs in the UK in 2017. This has indicated that one full charge of the entire goods vehicle fleet would require additional 2.16TWh of electricity, which is equivalent 0.65% of total UK electricity generation in 2018. With a full fleet of BELs and EVs, concerns are raised as UK grid and generation capacity might not able to cope with the new demand. However, it is estimated there are approximate 9million tonnes of goods lifted every year between the UK and the EU by goods vehicles (41). Hence, it is important to include comprehensive charging system in the EU, and hence full electrification of goods vehicle in the EU. Consequently, this will increase the electricity demand across the EU countries, and it is estimated the full electrification of goods vehicles in the EU would require 324TWh, which is approximately 10.59% of EU electricity generation in 2018. However, this estimation was made based on the average travel distance by the vehicles as the authors argue that not all goods vehicles require full charging for every driving cycle (25), (105). Hence, the realisation of full electrifications of goods vehicles in the EU or solely in the UK would require significant amount of financial investment to upgrade the electricity distribution networks and related infrastructures such as transformers and charging stations.

4.3.2 Charging Station

The majority of full battery electric vehicles operating today are either powered from off-board electricity delivered through conductive contact, such as busses with overhead wires or by electricity acquired from the grid and stored on-board in batteries (36). However, poor provision of charging infrastructures in the UK is one of the greatest barriers to growth of the domestic EV market (6). Currently, there are approximately 4,000 charge points in the UK, which are classed into 3 categories, standard chargers from 3kW, fast chargers ranged from 7kW to 22kW and rapid chargers that is above 22kW (106). However, the low number of charging station in the UK has indicated limited geographic coverage and the lack of rapid charging infrastructures. The scarcity can be observed from Table 13 below. Currently, most of the charging stations are relatively concentrated in Southern region, and Wales has the lowest number of charge points, which indicated the need to improve the charging infrastructure across the country (1), (6), (106).

	Number of charge points by region	People per charge point
North East	664	3,931
Scotland	743	7,127
Northern Ireland	185	9,789
South East	572	15,372
London	497	17,682
South West	262	20,382
West Midlands	206	27,549
North West	244	28,902
East Midlands	142	31,923
East	172	33,994
Yorkshire	103	51,825
Wales	31	98,806
Total	3,821	16,787

Table 13: Publicly Funded Charge Points (6).

However, it is important to ensure the distributions and the availability of the charging station based on local road freight activities and the range of BELs (107). Regions such as Yorkshire and Humber, East Anglia and the East midlands are the largest exporting regions in the UK. On the other hand, London, the South East and Scotland are the UK’s largest importing regions. Hence, the West Midlands region has become a hub for storage and distributions of the goods to other regions. As a result, these regions would require bigger capacity of charging station and higher power requirements for the charging of BELs, in comparison to other areas such as the North West, Wales and the North East regions (41). In general, routing-based analysis of the potential of BELs would be required to map the most important charging stations. However, further analysis of implications for the mapping of charging stations would require detailed spatial analysis and routing of the trips in the data, which is beyond the scope of this study.

Currently, the median plug-in duration is approximately 10hours 48minutes with majority of plug-in events are overnight charging. Most of the charging events are slightly more frequent on weekdays and tend to start in the late afternoon and evening, between 1700 and 1900. Conversely, the common plug-out time was in the morning between 0700 and 0900. This has indicated the charging events tend to fit around a work day as expected by DfT (106).

It is expected the common charging scenario for BELs could be charging overnight in the depot. Hence, assume the charging duration for goods vehicles is 10hours a day, a 32kW charger would be needed for LGV, 52kW charger for MFV and 96kW charger for HGV in this study. Freightliner claimed the 550kWh battery pack on its BEHGV, eCascadia can be recharged to around 80% within 90minutes (95), (102). This implies a 290kW charger is required to achieve this charging rate. Similar charger would shorten the charging duration of HGV in this study to approximately 3.3hours. However, such high power requirement of charging station would require the establishment of connections between medium voltage grid and charging stations, and an upgrade for the low resilience electricity distribution networks in remote areas (6), (25).

4.3.3 Potential Alternative Charging Technologies for BELs

4.3.3.1 Inductive Charging

On the contrary of conventional plug in charging systems via charging stations or charging points, inductive charging does not require wire or cable to transfer power. Hence, Inductive Power Transfer (IPT) is also defined as Wireless Power Transfer (WPT) or Electrical Vehicle Wireless Power Transfer (EVWPT) (43), (108). The charging method is based on the electromagnetic field created between the two inductively coupled coils, a primary one, the sender is connected to the grid, and the secondary coil, the receiver, is connected to the vehicle battery. The technology can be used for both stationary and dynamic charging. As shown in Figure 15, the sending device can be installed underground and charge the vehicles while they are parked or stopped. This system can be installed beneath bus stops, garages or packing lots, which allows drivers to position their vehicles over these energy sources, so that the charging operation automatically starts (1), (43), (108). IPT is considered safer and reliable technology in comparison to conductive charging. IPT does not require users to handle the power cords, and thus avoiding the risk of getting electrocuted (51), (109).

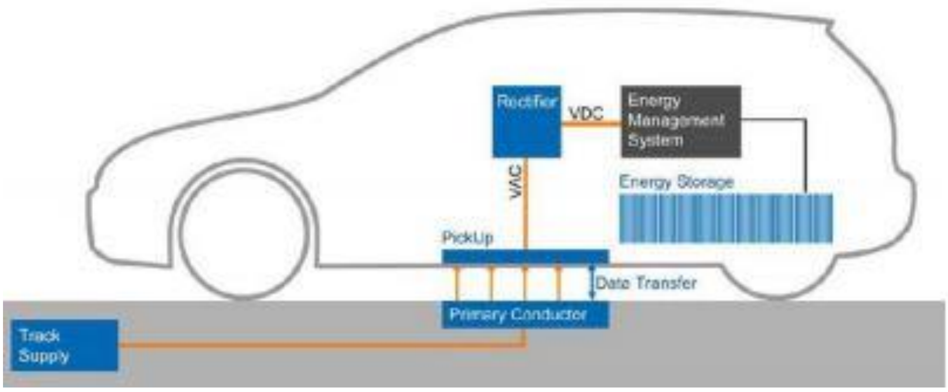


Figure 15: Stationary Inductive Charging System with Charging Plate Positioned Underground (43).

Stationary Inductive Charging can be classed into two forms, magnetic induction coupling and magnetic resonance coupling. The former technology has been used in electric toothbrushes, in case of EV charging application, it will require precise parking alignment to initiate the recharging operation. Induction coupling has the efficiency of approximately 100%, and thus higher cost effectiveness (43). Such recharging system has been deployed in the UK on bus routes in Milton Keynes, Glasgow and London (1). On the other hand, magnetic resonance coupling is currently still on development stage and it is more complex and expensive than magnetic induction coupling. However, it provides power over larger distances and can easily adapt to natural misalignment, which increases user convenience (43).

On the other hand, dynamic inductive charging involves an electromagnetic field placed under the roads and motorways (1), (43), (108). The EVs will be charged while moving on the roads, and thus the battery can be downsized and shorten the charging duration. This would effectively improve the driving cycle and energy efficiency of the EVs as battery weight and charging duration have been main obstacles of electrifications of vehicles (1), (109). Figure 16 has shown the conceptual design of dynamic inductive charging system. In the UK, the feasibility of trialling dynamic inductive charging has been examined, however the installation of the charging networks has been considered too expensive, though the system may offer value over long period of time (1). However, the receiving coil can be retrofitted to wide range of vehicles such as EVs, passenger vehicles and BELs, and thus the installation cost can be shared between different vehicle types (43). Currently, there is a few pilot projects in several countries such as Korea, Germany and US, in order to examine the performances and the feasibility of dynamic charging system. The system is believed to have the energy efficiency of 80 to 90%, however the efficiency is depending on the vehicle displacement and the core to core air gap (43), (109), (110).

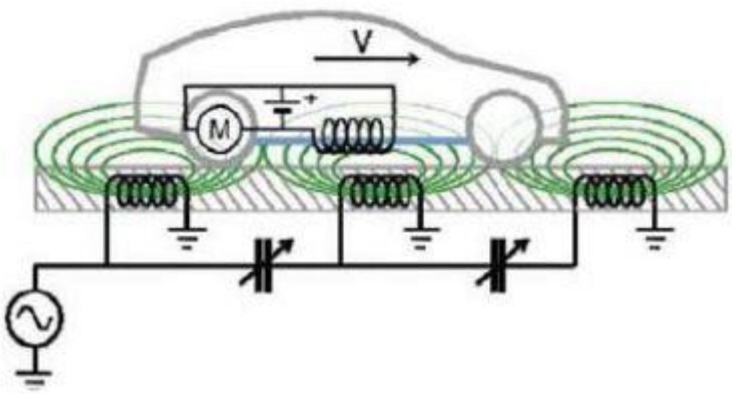


Figure 16: Dynamic Inductive Charging Technology (43).

In term of CO_2 savings, inductive charging system may have higher emissions than conventional plug-in charging system as it could further increase the intensity of daytime electricity demand during the traffic peak hours such as during the period from 0700 to 0900 in the morning and 1700 to 1900 in the late afternoon (4), (111), (112). However, the inductive charging system can avoid emitting more GHGs than conventional plug-in charging system with by shifting the charging induced demand to night time. As it is more likely for the users to use conductive charger to recharge their EVs in the house as inductive charging system is more expensive and complex than conductive charging system. This measure can further reduce the burden of inductive charging system on the road during the daytime and consequently results in lower GHG emissions from energy sector. Furthermore, the GHGs emissions from inductive charging system can be further reduced by improving its efficiency to 90%, the same level as conductive charging. This improvement is estimated to result in up to 6.3% less GHGs emissions from inductive charging system compared to conventional conductive charging system (112). However, DfT estimated the introduction of inductive charging system could reduce the total up to 40% of CO_2 emissions, with cumulative CO_2 savings over 20 years. Similarly, the emissions of NOx and PM could be reduced by 35% and 40% respectively. This estimation has also included the CO_2 emissions from power generation and taken account of the contributions from LGVs in the model (1). The inclusion of LGV into the estimation of GHG reductions may be the cause of significant differences between these studies.

4.3.3.2 Overhead Catenary

Overhead catenary technology, also known as Overhead Wired Power Transfer (OWPT), is an alternative charging technology to recharge the battery of vehicle on the road (1). This charging technology is applicable to HEVs and BELs, which can operate either with a combination of conventional ICE and electrical motor or full electric lorries that have minimum battery range of 50 to 100km (113). This would allow lower battery capacity required on the vehicles and hence lower battery weight, which ultimately avoiding payload or range reduction (43). When running on overhead wires, OWPT-compatible goods vehicle would have zero GHG emissions (1), (43). Overhead catenary wire systems have been widely used for trolley buses, light rail transit trains, and high-speed trains due to their high energy efficiency (36), (114). The catenary operation offers several advantages in comparison to other drivetrain concept, such as:

- Significant reduction on battery weight and hence higher payload available on the vehicles.
- Eliminate the issue of range anxiety as range will no longer be limited.
- Zero tailpipe emission from the vehicle when it is connected to the catenary.
- The technology is relatively robust and well-developed, thus easy to implement in comparison to other charging technologies.
- Does not require heavy transformer on-board due to the use of DC conductive charging, and hence frees up more payload capacity for goods vehicle.

Its application on HGVs was first introduced Siemens in 2012, where the concept of eHighway with its electric infrastructure was presented. The Swedish Transport

Administration was the first country to adopt this idea and tested a 2km of eHighway in Sandviken with the support from Siemens and Scania in 2016 as shown in Figure 16 (1), (113), (114). The conductor can connect automatically to the catenary system while travelling at the speed up to 90km/hr (1), (43), (114). The HGVs are modified with a diesel powerpack of 300kW, a 200kW PM motor and EDLC battery pack as energy storage (43).

Figure 17: Overhead Catenary Charging System

Similar pilot project was carried out in California, US to test its technical feasibility. This project is motivated by tightening emission legislations to meet air quality and the emission limit in Los Angeles area (43), (114). The catenary system connected from the ports of Los Angeles to Long Beach to assess the movement of HGVs and the near-dock rails facilities on regional level. The system utilises 750V DC power and is powered by DC substation with the capacity of 1.5MVA (114).

In term of carbon emission, the introduction of OWPT can significantly minimise the CO_2 emissions from the road freight transport sector. Though additional CO_2 emissions can be induced in electricity generation sector, the total carbon emissions from transport and electricity generations sectors can still be minimised due to the high efficiency of electric motors (1), (43), (113). It is estimated that OWPT can provide a total CO_2 savings of 60million tonnes of CO_2, which is equivalent 20% of CO_2 savings in the EU. However, this estimation is based on the assumptions that the additional electricity generated for OWPT are from conventional fossil fuels power plant and the emissions from well-to-tank from the diesel production are neglected (113). Hence, it is important to bring in a strong and effective energy transition towards renewable energy to expand the renewable energy generation capacity for OWPT. Such transition would significantly reduce the CO_2 emissions from road freight transports and energy sectors.

4.3.3.3 Battery Swap

As discussed in pervious section, the fast charging technology would require significant amount of financial investment for the upgrades and installations of the infrastructures. In addition, long charging duration would cause disruptions in the distributions of the goods in the country and pose further challenges to fleet management. Therefore, the concept of battery switching/swapping was introduced to tackle these issues. Battery swapping technology was proposed by an Israeli based company to overcome the long-charging duration issue of EVs and BELs and was introduced in Israel and Denmark by deploying nationwide battery-swapping stations and networks in both countries (115). The concept of battery swapping technology would require the vehicles to be designed for multiple daily battery pack swaps. Battery-swapping stations are deployed on key routes, where depleted batteries can be exchanged for recharged ones in the middle of long trips. The replacing time for the batteries would become competitive with conventional diesel refuelling time (115), (2).

Figure 18: EV Battery Swapping Station (116)

Battery swapping technology has several similarities with mobile phone contracts being widely implemented across the globe, and offers numerous advantages to the EVs and BELs owners, such as:

- Shorter charging time and longer driving cycle
- Lower capital costs of the EVs and BELs, as the battery cost will be eliminated, however, the swapping stations would require enough stock of batteries to ensure the availability of batteries for the user drivers.
- Easier maintenance and replacement for technical improvements of the battery pack.

Figure 19: Electric Scooter Battery Swapping Station in Taiwan (117).

This technology has been adopted by several countries since 2013. A fleet of electric buses in Qingdao, China, have utilised battery swapping, and similarly, a pilot program was launched in Quebec, Canada in 2018 (2), (118). Battery swapping technology was introduced to Taiwan for electric scooters in 2015 and now has expanded to Japan, France, Germany and Canada. In addition, battery swapping technology has also been adopted by India for bus and delivery van applications by the end of 2019 (2), (119).

As previously discussed, the electrification of road vehicles and the charging of EVs will increase the energy demand and hence the carbon emissions from power plants. However, unlike inductive and conductive charging system, the battery swapping and charging strategies would offer more flexibility in demand site management (120), (121). This is mainly due to decentralisation of charging strategy, which can avoid further increase of the daytime peak demand and concentrating the recharging in one certain period. In addition, load-shifting strategy by utilising the excess wind energy during the night time to recharge the batteries at battery swapping stations can minimise GHGs emissions due to induced energy demand from recharging the batteries (121). It is estimated with the use of demand site management and decentralised charging strategy, the battery swapping technology can reduce the GHGs emissions from transports and energy sectors by 2% (120).

4.3.4 High Charge/Discharge Rate

As aforementioned, the charging duration is a crucial factor in electrification of goods vehicles because long charging duration can significantly affect the operation of the road freight transportations and fleet management in road freight sectors. Thus, in order to avoid aforementioned issues, it is important to utilise opportunity charging. Opportunity charging only occurs during the loading, unloading of goods or during the driver's rest time (25). If the goods vehicles are set to be fully recharged in 45minutes during the compulsory rest after 4.5hours of driving, it would require a charger ranged from 425kW to 1300kW to fully charge the battery packs of LGV, MFV and HGV. this indicates that a connection of 10kV to the grid would be required and such system will need significant amount of financial investment on the upgrades for the infrastructures, such as cables and transformation stations (43). In addition, rapid charging is not ideal for LIB battery system due to the degradation of lithium electrodes, which is known as "plating" (56). This phenomenon can result in heat gain, efficiency losses and shortened battery lifespan (43). However, such issue does not exist in LIC battery system due to the use of electrodes materials. As previously mentioned, the electrode materials of LIC that is developed by Dubal and Gomez-Romero are rGO and N-CNPipes. This combination can avoid "plating" issue by avoiding the formation of lithium dendrites, which is the main cause of deterioration of LIB performances (61), (66). The use of graphene can effectively prevent the formation of lithium dendrites in the battery due to the formation of Li-carbon material and the unique graphitic carbon layers in the electrodes (66).

4.4 Challenges

4.4.1 Battery Technology

4.4.1.1 Development of Battery Technology

As discussed in previous chapter, though LIB battery system is currently being widely used as main power source for EVs, there are several drawbacks that have caused LIB system less attractive and limit the development of BELs. The limitations such as low power density, low upper operating voltage limit, low battery lifespan and safety concerns due to overheating issues, have discouraged the public and fleet operators from buying EVs and BELs. This has caused the manufacturers to consider other options as main power source for BELs. In addition, the fast battery charging would result in shorter the durability of LIB system due to "plating" issue (43). SC battery system may have inherited the characteristics that allow desirable performances for BELs, such as long lifecycle and high-power density, which allow higher acceleration, fast charge/discharge rate and longer battery durability. However, its extreme low energy density has made its applicability as energy storage for long haul applications not possible (12), (61), (63), (77). Hence, the focus has shifted to other battery technology such as Li-S, Li-air and LIC. However, the developments of Li-S and Li-air have been stagnant due to the technical challenges and it is believed their first prototypes will not happen until 2030 (43). In contrast, LIC system is widely believed to become mainstream energy storage for high power applications due to its high-energy and power densities, wider operating temperature range and long battery lifecycle, and its technology is better developed compared to former two battery technologies (12), (15), (16), (59), (61), (62). Figure 20 below has shown the roadmap for the developments of battery technology and infrastructure for BELs. Currently, the development of LIB has successfully improved its energy density to approximately 250Wh/kg, it has been widely used for EV applications. Though the research efforts have been put in to accelerate the developments of Li-S and Li-air batteries, it has been indicated that the commercialisation of both battery systems is expected around 2030. However, such estimation on the time frame is depending on multiple assumptions and can be significantly influenced by large uncertainties due to the technical challenges (43).

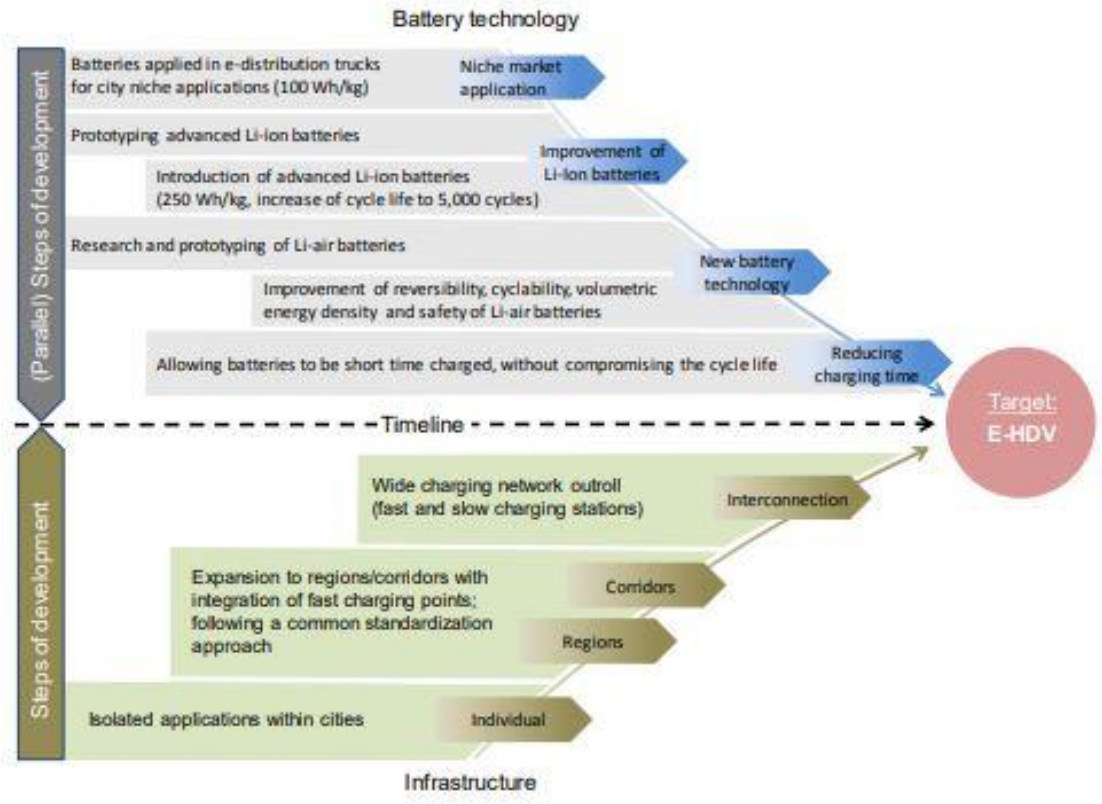


Figure 20: Battery Technology and Infrastructure Roadmap to 2050 (43).

4.4.1.2 Advanced Materials Industrial Synthesisability

However, current energy density of LIC is only 10Wh/kg, which is 25times lower than the set value in this study (76). It is important to notice that the current electrode materials in LIC are Activated Carbon (AC) based, however the LICs developed by Dubal and Gomez-Romero are graphene based, specifically reduced graphene oxide (rGO) and N-CNPipes (16), (66), (76). Evidently, the energy density of the battery is the main bottleneck in the development of battery technology as it dictates the crucial factors in EV application, the weight and volume of battery. Both factors decide the specifications of the vehicles such as range and acceleration rate, and they also dictate technical feasibility of BELs (43).

AC-based materials are dominant materials in LIC application because of its relatively low cost, its abundancy, its excellent electrochemical properties such as large specific surface area, pore volume and pore size distribution, which favour the chemical reaction of adsorption and desorption (59), (61), (122). However, the use of AC as the cathode material has limited the performances and the improvement potential of LICs. The limited surface area up to maximum 2500m^2/g of AC can only facilitate the capacitance of 120-130F/g in LIC (61). Furthermore, the presence of graphitic phase would limit the upper voltage limit the electrode can operate and leads to significant electrolyte degradation, and ultimately results in poor cyclic stability (74). Thus, the use of graphene-based materials as LIC electrodes materials was proposed. Dubal and Gomez-Romero has successful produced a LIC with high energy and power densities of 262Wh/kg at 400W/kg, by utilising N-CNPipes as anode material and rGO as cathode material (61), (66). Both nanocarbon materials can be easily produced and are more industrial scalable, and ultimately both materials can be produced at low costs in mass production (66). And hence, rGO is more widely utilised than pristine graphene as graphene is an expensive material and its lack of manufacturing scalability (64). Figure 21 below has shown the possible methods to synthesise graphene, graphene oxide and rGO from graphite. As it can be observed, rGO can be synthesised from graphene oxide with three different reduction processes, chemical, thermal and electrochemical reductions (64), (123). Chemically-Reduced Graphene Oxide (CRGO) is the product of reduction of graphene oxide with the use of strong reductants such as hydrazine monohydrate, sodium borohydride, hydroquinone and ascorbic acid. However, the biggest disadvantage of chemical reduction process is the yield of heteroatomic impurities which can affect the electronic structure of resulting rGO (123), (124), (125). In addition, reductants such as hydrazine and sodium borohydride can generate large quantities of gas during the reduction process and hence it would require high pressure equipment which ultimately would further increase the production cost of the material (124). Though chemical reduction is the most common method of producing rGO, electrochemical reduction pathway is also one of the common processes to synthesise rGO. Electrochemical reduction can avoid the use of dangerous reductants and the need of removing the impurities. This synthesis process involves depositing thin films of graphene oxide on the substrates such as glass and plastic, where electrodes were placed at the opposite ends of the film. The process starts with the run of sweep voltammetry in a buffer solution such as sodium phosphate and hydrogen ion solution (64), (123). However, electrochemical reduction has not been demonstrated on a large sample. Moreover, the deposition of rGO onto the electrodes is extremely difficult in industrial scale. Hence, electrochemical synthesis process is considered not industrial scalable even though the process has been proven to be extreme effective in reducing oxide functionality (64), (123), (124). Lastly, thermal reduction is another pathway to yield high quality rGO. This process utilises an autoclave at moderately high temperatures from approximately 90 to 200ºC to cause exfoliation of the stacked structure (124). It is estimated approximately 130MPa can be generated from the reaction at the temperature of 1000ºC. Such parameters would pose significant working hazards in industrial scale plant, which would require additional equipment to ensure the safety of the workers. Consequently, this would greatly increase the production costs of rGO. In addition, the release of carbon dioxide in the process would cause structural damage to rGO platelets, which can lead to approximately 30% loss of the products (123). However, thermal reduction seems to be the less environmental damaging and more industrial scalable compared to the former two rGO synthesis processes.

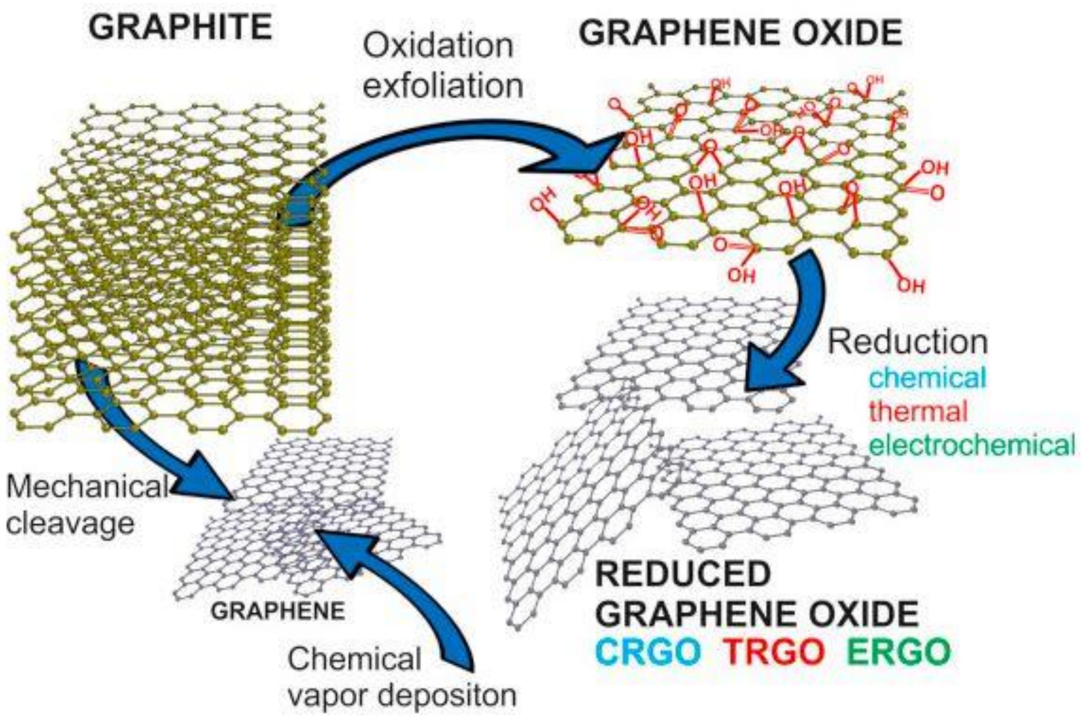


Figure 21: Schematic Illustration of Possible Synthesis Methods for Graphene and rGO from Graphite (64).

4.4.2 Costs

Costs have always been the main challenge in the electrification of vehicles. The upfront costs of purchasing an EV remain relatively high in comparison to ICE vehicles. Tesla Semi is expected to cost £110,000 for 300mile range and £140,000 for 500mile range, which is almost 3 times higher than the current price of ICE HGVs (43), (101). For the BYD T9SJ and Freightliner eCascadia, there is no available data indicating the prices of their batteries and BETs. Battery prices remain the main cost driving factor resulting in approximately 3.3 times higher production costs in comparison to ICE goods vehicles (43). In addition, LIC battery system is a relatively new and innovative design that was introduced in 2001 by Amatucci et al. (57), (61). Hence, the costs of LIC battery system on EV application or any large-scale power application remain uncertain. However, the cost of the battery system is expected to behave similarly as LIB system. Since, the introduction of LIB system, massive improvements have been made as the development has become more mature and advanced, learning rate for pack integration, industrial scale productions (Gigafactories) and increased energy density. As a result, the price of LIB has fallen by a factor of 4, which can be observed from Figure 22 (25), (126). The LIB cost curve from Figure 22 has demonstrated how the manufacturing cost of a battery system can be greatly reduced over time, regardless of its technology. Thus, it is reasonable to assume the same development for LIC battery system.

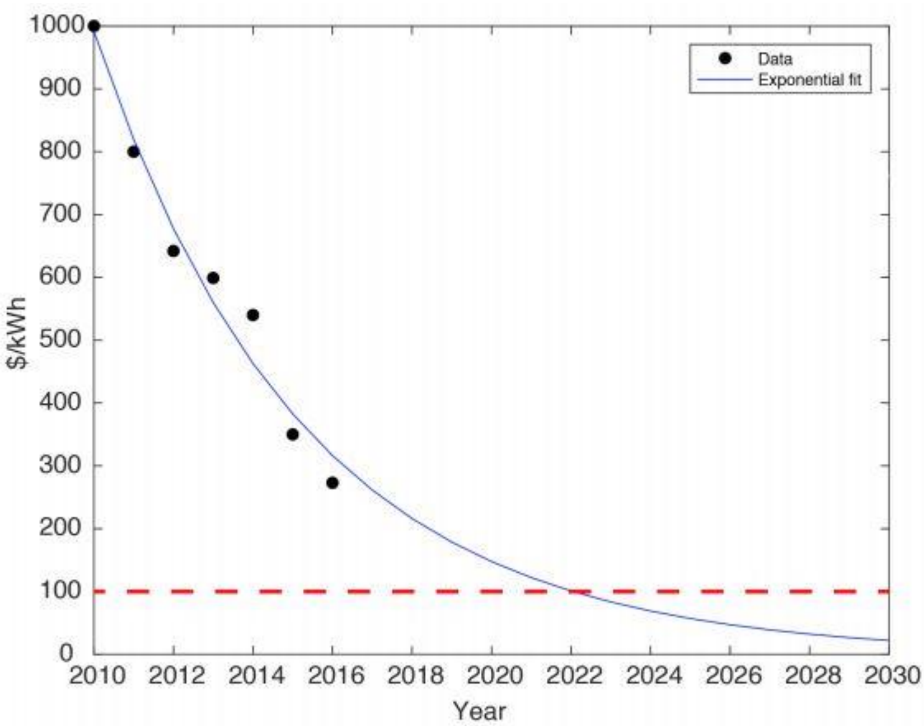


Figure 22: Manufacturing Cost of LIB since 2010 and Cost Prediction until 2030 (126).

Furthermore, the reductions on battery costs are expected to result in price drop of the EV. Consequently, it may cost less than conventional ICE vehicles and hydrogen fuel cell drivetrain, as Figure 23 demonstrated. However, the trajectory has failed to provide the costs breakdown of fuels, operations and maintenances, which are crucial factors in the decision of purchasing EVs and the replacement of the goods vehicle fleet (44). The prices for ICE vehicles are expected to rise due to strict legal requirements and additional tax introduced to encourage the vehicle manufacturers start electrifying their vehicles (1), (44).

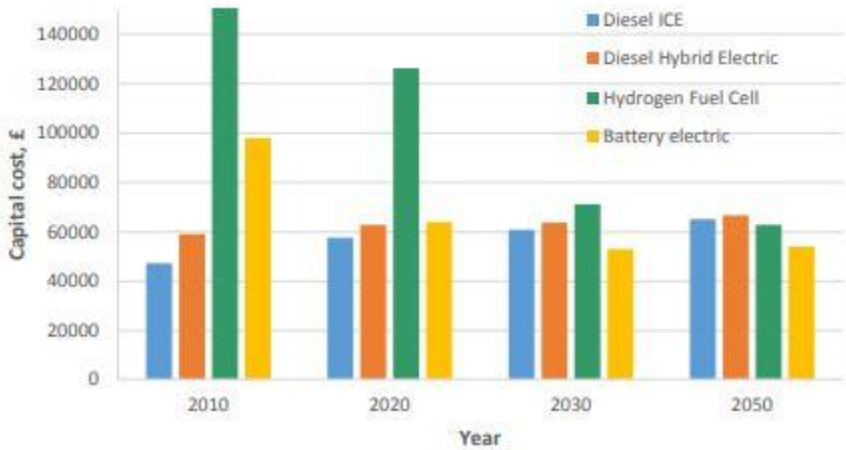


Figure 23: Average HGV Capital Costs Over Time by Vehicle Technology (1).

Figure 24 below has shown the average lifetime costs for hydrogen fuel cell drivetrain, BEHGV and hybrid electric vehicle in comparison to ICE HGV. The assessment is to predict and demonstrate how additional lifetime costs of different drivetrain technologies could fall over time. The assessment has projected that the costs of owning BEL will continue to fall, and BELs will become cheaper alternative to replace conventional diesel goods vehicles. However, it is important to note that this assessment has failed to address the uncertainties, such predictions of the costs were merely made based on assumptions on the predicted values for crucial parameters, such as future fuel prices, future battery costs and projected vehicle costs. Thus, the conclusions made from this assessment may change significantly due to outdated data and analysis (1). The battery pack costs for 700 and 1400kWh are estimated to cost $125,000 and $250,000 respectively (49). These estimated costs would take up to 94.4% of Tesla Semi selling price. However, such estimation has failed to acknowledge the high energy density LIB by Tesla and BYD, as both manufacturers have introduced LIB system for EV application with the energy densities of 250Wh/kg and 165Wh/kg correspondingly (25). This has indicated the data and information used in the analysis are outdated, and the analysis has failed to provide accurate insights of the developments of BELs and battery technology.

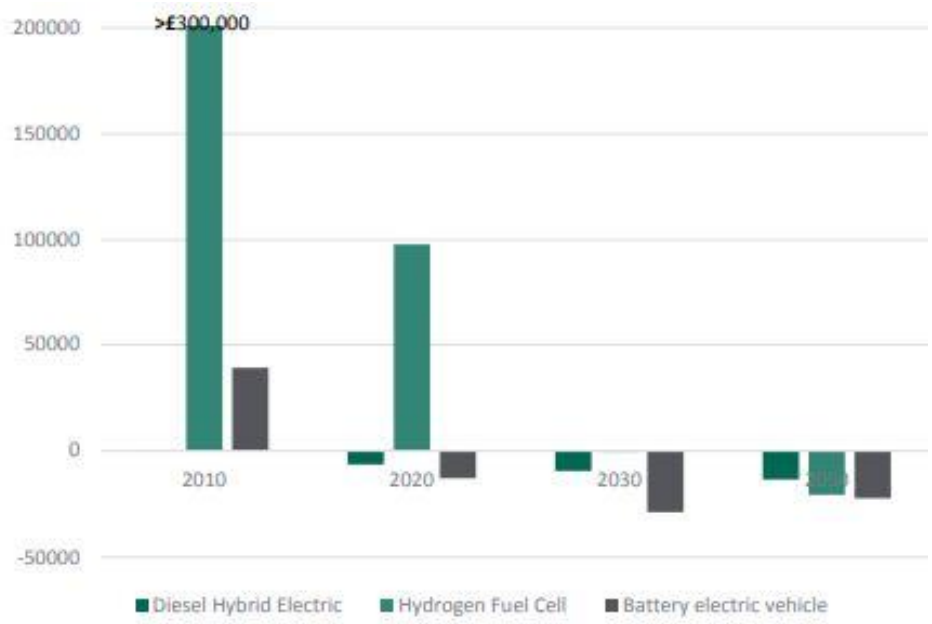


Figure 24: Average Lifetime Cost Premium for Low and Zero Emission Technologies Against Diesel HGV (1).

Though the UK government has offered tax exemptions and incentives for purchasing EVs and low emissions vehicles, however the purchase support has been proven to offer limited encouragement to public. In the UK, vehicle tax exemption is only available for EVs that are lower than £40,000 (21). In addition, the Government has announced substantial cuts to the Plug-in Grant Scheme, which further frustrates and undermines the efforts in attempting to achieve high EVs penetration in the UK (6). The current measures and available benefits for purchasing EVs have been only accessible to wealthier purchaser.

In addition, the constructions of charging infrastructures regardless of technology type, requires considerably amount of financial investments. The high-power requirement from the charging station would require a 10kV connection to the medium voltage grid, which could cost up to €108,000 per km (43). More detailed economic aspects of the infrastructures are briefly evaluated in the next session of this chapter. Furthermore, the lack of standardised and comprehensive charging and fuelling infrastructures has become the main obstacle for the road users to switch from fossil fuels ICE vehicles to EVs (44).

4.4.3 Infrastructures

4.4.3.1 Charging Station and Energy Generation Capacity

As previously discussed, the charging infrastructures in the UK are relatively poor provisioned and lack of capability for rapid charging. Though LIC battery system may allow high power charging for the EVs, the high-power requirement for the charging stations would require connections to medium voltage grid. Particularly in the remote areas where range anxiety can be intensified due to the lack of charging infrastructures. As discussed in previous chapter, the high-power requirement of charging stations for rapid charging can be an issue in remote areas due to their low voltage networks. Without appropriate planning and measures, this can lead to power outages because of excessive power demands. Hence, it is important for the government to upgrade local networks and power facilities to ensure stable electricity supply of charging stations. Some of business premises do not have the capacity of electricity supply to recharge their goods vehicle fleet simultaneously. Additionally, the costs for the connections and transformers would be expensive and could cost up to €108,000 per km, and ultimately entail significantly upgrade costs for businesses (1), (43). In addition, it is estimated a fleet of 12 BELs with 100kW chargers, the cost of the infrastructures could be as high as €1.5M as shown in Table 14 below (25). This has indicated the upfront technology costs for electric drive vehicles may be outweighed by the energy costs savings over the vehicle lifetime.

Item	Initial Stage Site	Mature Site
Civils	€64,000	€82,000
50kW chargers	€60,000 (for two)	€120,000 (for four)
100kW chargers	-	€240,000 (for four)
Charger installation	€10,000 (for two)	€40,000 (for eight)
Grid connection	€10,000	€345,000
Brownfield total	**€144,000**	**€827,000**
Access roads	€50,000	€50,000
Earthworks, Fencing, Surfacing, Drainage, Other Works	€100,000	€100,000
Additional professional fees	€33,000	€33,000
Grid Connection (cost saving)	-€5,000	-€5,000
Greenfield total	**€322,000**	**€1,005,000**

Table 14: Costs of Electric Charging Infrastructures (25).

Moreover, the high upfront cost of the infrastructures has been one of the main barriers in the development of charging infrastructures. It is estimated that the establishment of infrastructures would cost up to $12.5billion, which is equivalent £11billion for the full electrification of goods vehicle in the UK (127). However, without the financial support from the government, the development of charging infrastructures has been stagnant. The UK government has been relatively passive in the transition to electrification of vehicles, this is mainly due to the attitude of the government believing the electrification of road transport vehicles should be industrial and consumer led (6). Evidently, the lack of infrastructures is the main barrier for the fleet operators to replace their conventional diesel goods vehicles with BELs. This has implied that the government needs to take the initiative to encourage the purchase of EVs, and to ensure the development of infrastructures is at least being carried out simultaneously as the electrification of goods vehicles and the introduction of BELs.

In addition, the lack of standardisation of charging infrastructures is one of the hinderance in the electrification of goods vehicles. Due to the high intensity of road freight activities across the EU countries, it is utter most important for the governments across the EU countries to provide standardised and comprehensive charging network systems. The lack of standardisation of charging infrastructures can lead to variations in physical charging connectors, network memberships and payment methods, which have been preventing EVs users from accessing the charge points in the UK (6). Though according to the standard IEC 62196-2, charging connectors are now standardised worldwide, the standardisation in the EU has yet to be completed. This is mainly due to different laws and safety requirements in each country, and the infrastructures and connectors are being developed by different companies in the EU (108).

Furthermore, the electrification of goods vehicles would cause significant increase in electrical demand in the UK. In order to meet the demand, it is important to expand the power generation capacity in the UK. Regardless of the level of new capacity required to supply BELs, it is crucial to utilise low carbon power generations or renewable energy systems in order to ensure the core aim of reducing GHGs emissions from road freight transport. In addition, the introduction of smart charging technologies, vehicle to grid technology and incentives to charge vehicle at off-peak times can shift and lower the electricity peak demand (6).

4.4.3.2 Battery Swap

Though the battery swap technology may significantly reduce the upfront cost of BELs, the swapping station will instead increase due to the amount of batteries required for the stock. It is estimated that a swapping station would cost approximately $3million per station (43), (115). Hence, the companies may be reluctant to invest more unless there is a significant demand for EVs. However, as aforementioned, the consumers are reluctant to purchase EVs unless the infrastructures are well established and can be easily accessed. Hence, it is important for the government to step in and provide funding and incentive supports to the companies in order to establish nationwide battery swapping systems. In addition, the batteries need to be standardised across manufacturers and swapping stations. The vehicle and station designs are required to be standardised to ensure the accessibility of all EV users. However, the standardisation of the batteries may seem not possible as this requires all the EV designs, including BELs to allow the batteries to be at the same location. This would be very difficult to be accomplished for LGVs and HGVs (43). Moreover, current developments of battery swapping technology and EVs contain numerous uncertainties that the vehicle manufacturers are focusing on different charging technologies. This can be observed as Tesla obsoleted its battery swap pilot program in 2016 and started to focus on its supercharger (43), (128). Additionally, battery swapping technology is considered not feasible in long haul application due to shear weight of the battery. Furthermore, battery swapping stations will need to implement smart charging and appropriate management to avoid recharging depleted batteries at the same time, this may lead to heavy load on the grid and overloading the transformers (115).

4.4.3.3 Stationary Inductive Charging

In comparison to battery swapping and rapid conductive charging, stationary inductive charging technology is relatively well-developed. Several pilot projects have been launched in public transport sector of several countries, such as Germany, Japan, New Zealand and the Netherlands, as the passenger vehicles drive on fixed route and make stops frequently (1), (43), (114). However, it is very unlikely that this technology can lead to wide-scale implementation of BELs. Stationary inductive charging technology does not solve the issues like limited range and ‘range anxiety’, as most of the goods vehicles spend more time travelling on the road than station in one location. In addition, it requires precise alignment with the charging pad to be recharged, which may increase

(43), (114). Such technology has been proven to be suitable for frequent stop-and-start operation, such as passenger vehicles and garbage trucks. Moreover, stationary inductive charging system would cost more than conventional conductive charging systems. The average cost for stationary inductive charging is approximately £300/kW to £450/kW (114). However, it is believed that stationary inductive charging can be combined with other charging technology such as dynamic inductive charging and overhead catenary technology, to minimise the power requirement of the charging stations (43). As the goods vehicles can still be recharged during the loading/unloading of the goods or the vehicles are parked in the depot overnight. This measure would effectively shift the demand to off-peak period and minimise the increase of peak demand induced by the introduction of BELs.

4.4.3.4 Dynamic Inductive Charging

Dynamic Inductive Charging may have more benefits than its counter-part, stationary inductive charging as it allows the vehicle batteries to be recharged while travelling on the road. This would solve the 'range anxiety' of EVs and significantly improve the range of EVs. Though such system has been introduced to part of the motorway in the UK to assess its effectiveness and deployment requirements, the system has been proven to be too expensive for full implementation. The installation cost in the UK is estimated to be between £1.7 and £5.5million per mile (1), (114). In addition, dynamic inductive charging may require high frequency maintenance due to pulsating charging power that caused by frequent switching on-and-off of the wireless power supply. This may further increase the already high operation and maintenance (O&M) costs of the charging system, which can be as high as 1% of initial upfront cost, and lead to higher maintenance costs for the motorway (114). Furthermore, dynamic inductive charging can further increase the power peak demand, as its charging mode is depending on the traffic flow. Therefore, the transformers may be overloaded during the peak-hour period and ultimately affects the stability of the grid negatively (111), (112), (114). Given the state of testing and pilot projects in various countries, dynamic inductive charging may require long period of time to assess its effectiveness and to improve the robustness of the technology before the large-scale implementation.

4.4.3.5 *Overhead Catenary*

Similar as the dynamic inductive charging, the main barrier of implementing overhead catenary systems is the costs, which can be broken down into two parts, power supply infrastructure cost and roadside installation cost. The high cost of implementation can be observed from the pilot project in Sweden, the high installation cost forced the Swedish Transport Administration to only install the system on one land (114). It is estimated that the overhead catenary systems can cost up to £4million per mile. Therefore, the fleet operators are certainly not able to afford it without government funding on the catenary infrastructure and subsidies for retrofitting the vehicles. In addition, unlike dynamic inductive charging, overhead catenary system will only allow the electrified goods vehicles to be recharged due to the height of the catenary. This implies that the installation costs cannot be shared between the vehicle types. Furthermore, overhead catenary systems may increase the peak demand of the electricity as the charging pattern is depending on the traffic flow. And hence, it is important to introduce appropriate fleet management to shift the charging to off-peak period. Currently, overhead catenary systems are being launched as pilot project in Sweden and US to assess its feasibility and effectiveness. However, it is very likely that overhead catenary systems will take a long period of time for further study and improvement before its large-scale implementation.

5 Future Work

The scope of this work is limited to a technical feasibility study on using LIC battery system as the main power source for the goods vehicles. Given that LIC battery system is relatively new and innovate technology, the economic aspects of this battery system are not being investigated. Hence, it is important to investigate the production cost of LIC with advanced material such as rGO and N-CNPipes and the cost of the battery system on EV application. In addition, it is crucial to analyse the lifetime cost of the battery, which was not considered and investigated in this study.

The architecture and the design of LIC battery pack is not being investigated as LIC battery system is still in early stage of development, and hence it is impossible to consider the design of LIC battery pack and its design on goods vehicles. However, the development of LIC should be closely monitored and investigated once the technology becomes more mature and well-developed for large scale application.

Though this report is to investigate the feasibility of using LIC battery system with high energy and power densities on BELs, it is important to investigate the use of solar panels or solar roof on top of vehicles. Additionally, its impacts on the performances of the vehicles and battery system from different locations should be modelled and analysed.

Further study on the impact of alternative charging technology, such as dynamic inductive charging and overhead catenary system on the reduction of vehicle battery weights should be considered. As the battery weight and volume are crucial factors in EV design, and this may significantly change the outcome of the study.

Finally, other battery technology such as LIB, Li-S and Li-air should be closely monitored and studied for further analysis as the development of battery technology has been proven to be rapid. And hence, it is important to investigate and compare their performances on EV application. Similarly, the electrodes materials should also be closely monitored for further study as it is closely related to energy density of battery.

6 Conclusion

The investigation of LIC battery system as main power source for BELs has concluded that it is technically feasible. Though the payload capacities of goods vehicles are inevitably reduced, the additional weights induced from the battery system are acceptable by the industrial representatives. LIC battery system has been evaluated to be a suitable energy storage for high power electric vehicle application due to its long lifecycle, excellent energy and power densities, and its capability to operate in high temperature and high voltage.

Secondly, current state-of-the-art of LIC battery system is relatively new and hence relatively expensive. The utilisation of advanced materials such as rGOs and graphene as electrodes materials introduces a high performance LIC with the energy density of 262Wh/kg and power density of 450W/kg. Moreover, it is expected that the production cost of LIC battery system will fall drastically just as LIB system due to industrial mass production and well-developed manufacturing processes.

Thirdly, thermal reduction process is considered as the most industrial scalable and environment friendly synthesis pathway for the preparation of rGO compared to chemical and electrochemical pathways. However, the technology and synthesis method would require more research effort and time to be well-developed before mass production for battery application.

Fourthly, with the combinations of power charging technology and optimum vehicle design, the volume and the mass of the battery system can be further minimised. First, improvements on rolling resistance, aerodynamic coefficient and electric motor can significantly reduce the energy losses due to frictional and aerodynamic drag forces. As a result, the battery capacity required will be lower and hence the mass and the volume of the battery system.

A 100kW high power charger would be required in order to fully recharge the goods vehicle during the 45minutes compulsory break. The high-power demand from the chargers and the charging stations would require connections to medium voltage grid. However, the high-power requirements for the charging may overload the transformers and the less resilience distribution networks, which can lead to power outages in local region. Furthermore, the local business premises may not have the electricity supply to recharge the vehicles. Hence, it is important for the government to provide funding and subsidies to upgrade the local electricity distribution networks, and to establish accessible and comprehensive infrastructures for EV users.

Though stationary inductive charging is relatively well-developed and has been widely implemented in urban public transport sector, it has shown poor suitability for long-haul application. This technology has shown it is more effective for passenger vehicles and garbage trucks which operate in frequent start-and-stop mode and travel on fixed routes.

Furthermore, battery swap technology can be considered as least favourable charging option as it offers very limited advantages in comparison to inductive charging and overhead catenary technology. This is primarily due to its high upfront technology cost for battery swapping station. Moreover, it requires the designs of EVs and battery systems to be standardised, which is not possible for the current stage of developments for EVs and vehicle batteries due to the large uncertainties on the feasibility of the technology from the manufacturers.

Dynamic inductive charging and overhead catenary on the motorway would free up more payload capacity by reducing battery weight and capacity without sacrificing the vehicle range. Both technologies would allow the vehicles to be charged while travelling on the road and have shown great potential to catalyse the electrification of goods vehicles. However, both technologies require relatively high upfront costs for infrastructures installation and to retrofit the vehicles. This drawback has demonstrated that both technologies would require long period time for cost reduction and to be well-developed for their performances and reliabilities before large-scale implementation.

Finally, it is unclear on the exact timeframe for electrification of goods vehicles as most of the technologies are still in the early stage of development and the performances of LIC battery pack on the vehicles and the charging technologies are still being investigated. However, it is evident that the high performance LIC battery system are technical feasible and applicable on BEL application due to its acceptable weight. Moreover, the battery weight on the vehicle can be further reduced by implementing dynamic inductive charging or overhead catenary systems.

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