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Techno-economic and environmental comparison between battery and fuel cell electric vehicles

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Presented for MBA

This project is entirely the original work of student registration number 22759525. I declare that this dissertation is my own work, and that where material is obtained from published or unpublished works, this has been fully acknowledged in the references. This dissertation may include material of my own work from a research proposal that has been previously submitted for assessment for this programme.

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Abstract

This research presents a techno-economic and environmental comparison between battery electric vehicles and fuel cell electric vehicles that automakers can consider when defining business strategies. The results indicate that there are some limiting factors that might hinder the market penetration of these technologies due to material resources scarcity and limited power generation capacity. Newer business models are expected to change the automotive market. Mobility as a service and connected autonomous vehicles are likely to change the value proposition offered by automakers and it will make more difficult to deliver differentiating factors. Reliability of both technologies is excellent but faster refuelling time of FCEV offers a differentiation factor that could be most appreciated by commercial fleets' operators. Average BEV cost double than FCEV but the cost differential is narrowing down fast. Range anxiety is one of the main concerns for BEV customers; however, with current 60 kWh batteries, range is enough for most users most of times. The way of financing the procurement of electric vehicles can make a difference in the selection of the technology. Automakers, must combine financing approaches, strategies of differentiation and specific value propositions depending on whether the vehicles are sold to private or corporative clients.

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Glossary

BEV	Battery electric vehicle
CAV	Connected autonomous vehicles
CCS	Carbon capture and storage technologies
CO_2e	CO_2 equivalent
COP21	Conference of Paris 2021
EPA	Environmental Protection Agency
FAME	Biodiesel (fatty acid methyl esters)
FC	Fuel cell
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
HRS	Hydrogen refuelling station
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
LCA	Life cycle analysis
Li-ion	Lithium-ion
MaaS	Mobility as a service
NEDC	New European driving cycle
NPTCO	Net present total cost of ownership
PEMFC	proton exchange membrane fuel cell
PoP	Point of Production
PoU	Point of Use
SMR	Steam Methane Reforming
SOFC	solid oxide fuel cell
TTW	Tank-to-well
UK	United Kingdom
VAC	Alternate current voltage
VDC	Direct current voltage
WTT	Well-to-tank
WTW	Well-to-wheel

Other acronyms

CO	Monoxide of carbon
CO_2	Dioxide of carbon
Li	Lithium
Li_2CO_3	Lithium carbonate
NOX	Nitrogen oxides
PaHs	Polycyclic aromatic hydrocarbons
PM_X	Particulate matter
Pt	Platinum
SO_2	Dioxide of sulphur
VOC	Volatile organic compounds

Units of weight, power, energy and pressure

g, Kg, t, Mt	gram, kilogram, ton, million ton
kW, MW, GW, TW	kilowatt, megawatt, gigawatt, terawatt
kWh, MWh, GWh, TWh	kilowatt-hour, megawatt-hour, gigawatt-hour, terawatt-hour
MJ	Mega joule
MPa	Mega pascal

Table of Contents

Table of Appendices

List of Tables

List of Figures

1. Introduction

Currently, almost 95% of vehicles worldwide are powered by internal combustion engines (ICE) fed by fossil fuels. These are responsible for most UK GHG emissions and represent a substantial source of air quality pollution in urban areas. It is accepted by the academic community that carbon emissions lead to climate change (IPCC, 2013) and it has been proven that air pollution is one of the main causes of premature death[1] and other health related externalities. As a result, of both, there is a growing interest by governments worldwide in transitioning to more environmentally friendly vehicle technologies. Despite several iterations of the Euro Emissions Standards and similar ones abroad, ICE vehicles still emit pollutants even with emission reduction technologies and they will continue to do so in the future. Furthermore, ICE powertrains are very inefficient (~30-35%) and their maximum theoretical efficiency is well beyond electric powertrains. Several candidates have the potential to replace ICE; however, only battery electric vehicles (BEV) and hydrogen fuel cell vehicles (FCEV) produce zero emissions at the point of use and have production pathways that can yield the lowest greenhouse gas (GHG) well-to-tank emissions of all. Moreover, these vehicles are quiet and can mitigate noise pollution.

This study excludes hybrid powertrains for two main reasons: they are more complex than vehicles with a single technology and therefore more expensive; and secondly because those fitted with an ICE still generate air quality and GHG emissions. Under that approach, BEV are vehicles that include typically lithium-ion batteries that are recharged in the national grid. However, distributed power and auto generation can also be used to produce that energy. BEV present the highest powertrain efficiency; however, they rely on batteries with limited amounts of reserves (e.g. Lithium) and on very limited geographical zones. This could drive prices up with higher vehicle penetration rates and it could create geo-political tensions with supplying countries. Additionally, the national grid is not ready yet to deal with the increase of power required by these newer vehicles.

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[1] It has been estimated that around 29,000 people die each year in the UK due to air quality pollution (COMEAP, 2010).

FCEV are powered by a proton exchange membrane fuel cells (PEMFC) fed by hydrogen gas. Other fuel cell powertrains such solid oxide fuel cells (SOFCs) can be fed by biofuels and biogases. However, these are excluded from this study as there are no commercially available vehicles just yet and no data exists in regards to their performance or cost. Hydrogen is an energy carrier and needs to be produced from primary energy sources. As such, there are energy losses that result in a poorer energy balance than BEVs. However, hydrogen present multiple advantages. There is a large range of potential production pathways with varying well-to-wheel emissions and water footprints. Those based on renewables or nuclear power can yield very low GHG emissions. In addition, the feedstocks that can be used include fossil fuels (e.g. natural gas, coal, etc.), biomass or water in combination with renewables. This versatility enables any country to produce a fuel suitable for transport, potentially eliminating the need to rely on foreign supply. This contribution to energy security is one of the main strengths of hydrogen and explains the interest on developing a hydrogen economy and considering FCEV over BEV.

This study focuses on private cars (class 1 vehicles); though, references are made to commercial fleets (taxis, renting companies, car-pooling and car-sharing), as these present different operating needs that can switch the adequacy of one technology towards another. The relevance of each type of vehicle in a future with autonomous vehicles is also discussed.

1.1. Aims of this research

This study compares BEV and FCEV as both powertrain technologies stand in 2017. The main aim is to help organisations to identify the key economic, environmental and technical selling points that may entice prospective consumers of zero emissions vehicles today. This dissertation calculates the total cost of ownership, lifecycle GHG and air quality emissions, and it presents the key technical differences between both powertrains and whether these predetermine specific consumers. This also involves an assessment of the material needs in regards to the key main raw materials used to manufacture each powertrain (lithium for batteries and platinum for fuel cells). This study also provides insights into policy making in regards to strategic infrastructure deployment and the support needed to deliver UK GHG targets for transport, as well as some of the current and planned initiatives that can governments around the globe are pursuing in support of electric vehicles.

This study also considers the likelihood of BEV or FCEV becoming the dominant technology by 2050. The reason for this is that the only way for transport to meet its 2050 targets, as agreed by the UK Government in the COP21, while reducing air quality emissions, is by using electric powertrains. The reason for focusing on 2050 is that it would be too challenging to deploy the entire infrastructure needed before then.

1.2. Research questions

Currently the prices of BEV and FCEV are considerably more expensive than conventional cars. However, the total cost of ownership is less so. By 2050, it is likely that these will reach parity with ICE vehicles. This does exclude the costs of externalities; if these were internalised, then parity could be reached much sooner.

This study will respond to the following research questions:

1. What is the current net present total cost of ownership of BEV and FCEV in 2017?
2. What are the GHG lifecycle emissions of such vehicles, including manufacturing and operations?
3. What technology is likely to prevail in the 2050 scenario, in regards to infrastructure deployment and raw materials reserves?
4. How automakers can adapt their strategies to take advantage of shift towards electric mobility.

1.3. Structure of this dissertation

Chapter 1 has introduced the aims of this research and it has justified its importance globally and for the UK in particular.

Chapter 2 introduces the technical, environmental and commercial context under which BEV and FCEV operate. This chapter presents the connection between fossil fuels, GHG emissions and climate change is explained. Similarly, the link between outdoor pollution and human health is introduced. This chapter also describes the role of hydrogen as a fuel for transport, several of its production pathways and its carbon footprints. BEV and FCEV characteristics are also illustrated, with a focus on batteries and fuel cells.

Chapter 3 reviews the academic literature in the areas of strategy, innovation and innovation management. The applications of the strategic and innovation models and frameworks explained in this chapter appear in the appendices.

This research is based on the case study of a number of companies. Chapter 4 explains and justifies the validity of case studies as a valid research method for this type of work.

Chapter 5 presents the results of the different models applied. This includes the total costs of ownership of the vehicles in 2017, the GHG emissions from each powertrain technology, as well as several performance indicators of different vehicle. This chapter also discusses some of the constraints that may constraint the production of BEV and FCEV. The methodology explaining how to calculate net present costs, total costs of ownership and life cycle analysis are detailed in the appendix.

Chapter 6 discusses the findings and how the particular needs of different users (private or commercial) influence the suitability of each technology.

In the last chapter, the main conclusions are highlighted. Chapter 7 also includes recommendations for further research and it reveals the main limitations of this study.

2. Context

This chapter introduces the context under which vehicle manufacturers work, as this is necessary to develop the strategies that will allow them to operate in a new market where conventional powertrains are being replaced for alternative ones that produce fewer emissions. This chapter introduces the linkage between internal combustion engine vehicles (ICEV) and climate change as well as the connexion between vehicles and air quality pollution and human health, both being powerful reasons to justify the need for BEV and FCEV. This chapter also illustrates how these technologies work, their technical characteristics and it explains the main challenges that each of these present based on their respective supply chains.

2.1. Reasons for phasing out ICE vehicles

Virtually all energy in transport depends on fossil fuels (Barnier, 2007) (IEA, 2016) to such an extent that 43% of the global oil demand is consumed by vehicles; almost 60% of this is gasoline and the rest diesel (OECD/IEA, 2014). Currently, just 4% of energy comes from biofuels (IEA, 2016), a percentage that is likely to increase in the future due to legislation such as the Renewable Transport Fuel Directive (European Commission, 2011), a policy that aims at reducing the GHG intensity of fuels by 10% by 2020 by rising the percentage of biofuels in conventional road fuels. Worldwide, transport is responsible for 11% of total anthropogenic GHG emissions (IPCC, 2014), a percentage that increases to 21% in the UK (BEIS, 2017a). From these, passenger cars with 69 MtCO_2e represent almost 60% (Figure *1*), just 5% less than the emissions produced in 1990, despite successive technology improvements, mainly due to higher rates of vehicle ownership.

Petrol and diesel are made of hydrocarbon chains than when burned within internal combustion engines (ICE), they produce a series of gases (Equation *1*), some of which are considered to have an impact on climate change and others on air quality pollution. Road fuels produce CO_2, a GHG gas that contribute to climate change due to its positive radiative forcing likely to rise the average temperature of the planet by up to 4°C by the end of the century (IPCC, 2013). This could lead to the melting of the ice poles and permafrost, leading to sea level rises of up to 1 metre. As a substantial percentage of the world's population lives closer than 100km from the sea, this and episodes of extreme weather events are likely to generate considerable damages to people's habitat and ecosystems and could lead to massive migration waves and flora and fauna extinctions. The IPCC (2014) considers that to avoid the most dangerous effects of climate change, temperatures must be kept well below a 2°C increase. For this reason, Governments worldwide are committed to put in place the right policies to reduce their GHG emissions. The EU for example aims at GHG emissions reductions of around 80% by 2050, compared to 1990 levels (Table *1*). The targets for transport are less ambitious as it is accepted that it is more difficult to decarbonise this sector due to the high energy density of fossil fuels and the fact that alternatives still have to overcome basic challenges. In the UK, there are interim targets known as 'Carbon Budgets' that specify the GHG savings necessary to meet the 2050 goals (Figure 2). These targets are known as the 'Carbon Budgets' and comprise a series of initiatives that are expected to deliver 431 $MtCO_2e$ fewer emissions in the period up to 2028-2032 (Fifth Carbon Budget); almost 40% coming from transport.

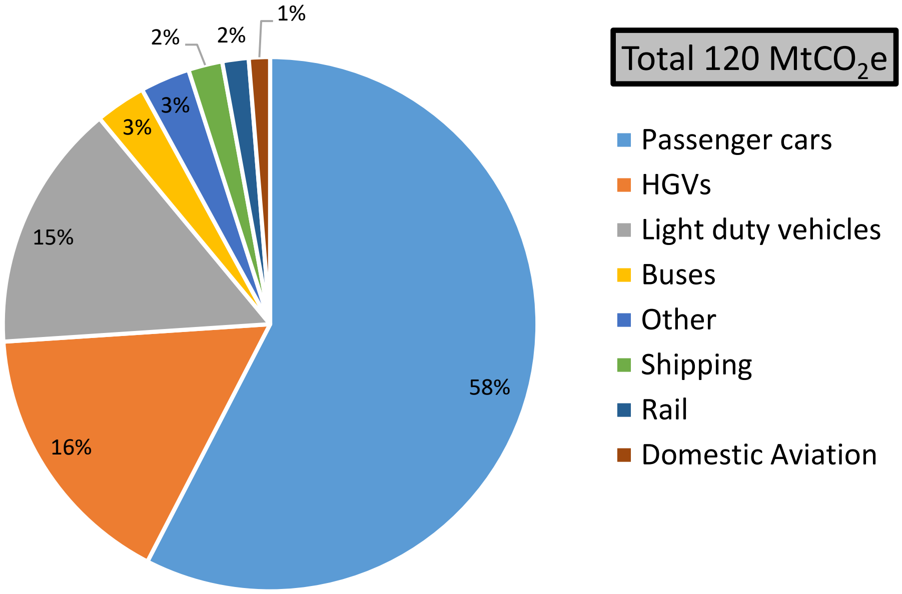

Figure 1. UK GHG emissions from Transport. Adapted from: BEIS (2017a).

Equation 1. Compounds produced in the combustion of vehicle fuels (diesel). Adapted from: Velazquez Abad (2016).

$$C_XH_Y + Air = H_2O + CO_2 + CO + PaHs + NO_X + PM_X + SO_2 + VOC$$

Table 1. GHG emissions reductions to be achieved by different sectors in the EU by 2030 and 2050 to meet climate change targets. Adapted from: European Commission (2011b).

GHG reductions compared to 1990	**2030**	**2050**
Total	-40 to -44%	-79 to -82%
Sectors		
Power (CO_2)	-54 to -68%	-93 to -99%
Industry (CO_2)	-34 to -40%	-83 to -87%
Transport (incl. CO2 aviation, excl. maritime)	+20 to -9%	-54 to -67%
Residential and services (CO_2)	-37 to -53%	-88 to-91%
Agriculture (non-CO_2)	-36 to -37%	-42 to -49%
Other non-CO_2 emissions	-72 to -73%	-70 to -78%

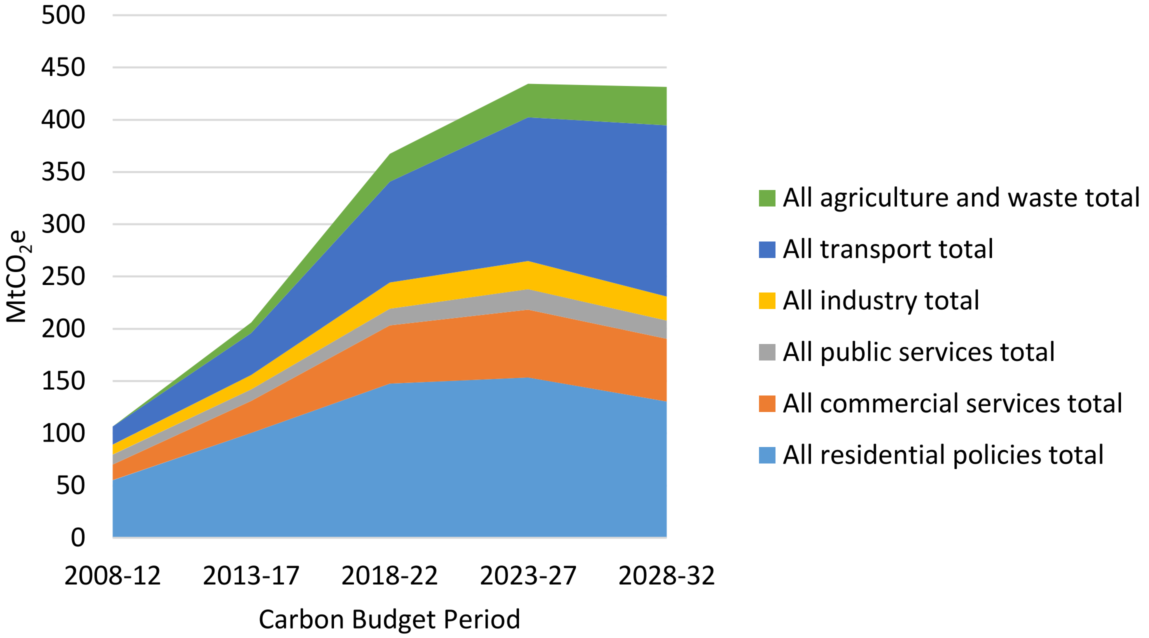

Figure 2. UK GHG Savings from policies by each sector according to the interim 'Carbon Budgets'. Adapted from DECC (2015).

ICE running with biofuels are not a suitable solution for delivering sustainable transport because despite that they can reduce GHG emissions they can also increase the amount of air quality pollution (Table *2*) and for this reason BEV and FCEV are being considered as better alternatives. The pollutants that appear in Equation 1 ($CO+PaHs+NO_X+PM_X+SO_2+VOC$) have a negative impact on human health[2] including respiratory and cardio-vascular issues (EEA, 2014; WHO, 2013). The amount of deaths (Table *3*) has been valued at €330-940 bn and the working

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[2] A list of the effects of these pollutants on human health is illustrated in *Table 20* in Appendix I.

days lost to another €15 bn of economic losses in the EU (EEA, 2014). The WHO (2012) classifies diesel engine exhausts as carcinogenic to humans and it estimated that around 223,000 people died worldwide from lung cancer in 2010 due to air pollution (WHO, 2013). Besides, air borne pollutants also damage the ecosystem. For example, NO_X contributes to water eutrophication and SO_2 to acid rain, which harms plants, decreases crop yields and it can damage the built environment as well. Currently, the costs of these externalities are not reflected in the price of fuels; though, it is projected that these are going to grow exponentially in the future (OECD, 2016). For all these reasons, there has been a shift in public policy to constrain the use of vehicles powered by fossil fuels. Examples of these initiatives include the ban imposed to diesel vehicles from Paris, Madrid and Mexico City by 2025 (C40 Cities, 2016). In the meantime, Madrid and Paris restrict the circulation of some cars in the city centre when air quality levels exceed a certain threshold (Ayuntamiento de Madrid, 2017). London will impose from October 2017 a £10/day Emission Surcharge (also known as the 'T-Charge') to those vehicles that do not meet a minimum exhaust emission standard (C40 Cities, 2017).

Table 2. Emission scaling factor for some biofuels compared to a baseline diesel heavy-duty vehicle. Source: Defra (2011).

Biofuel	**HC**	**CO**	**NO_X**	**PM_X**
FAME B100	0.31	0.66	1.08	0.62
Virgin Plant Oil B100	1.5	1.5	1.0	1.5
Biogas	0.65	0.83	0.5	0.3

Table 3. Deaths due to outdoor air quality pollution.

Area	**Deaths**	**Reference**
Worldwide	3.7 million	WHO (2014)
EU	200,000 520,000	WHO (2014) EEA (2016)
UK	29,000	COMEAP (2010)

In Europe, new vehicles must meet the Euro Emissions Standard Directive. This Directive limits the amount of pollutants that vehicles can emit. The latest Euro 6 is much more stringent than previous iterations; nevertheless, emissions from cars are still so high that the limits regulated by the EU Air Quality Directive are exceeded continuously in the largest urban areas. The reason for this is triple. On one hand, diesel vehicles are fitted with exhaust gas catalytic converters that minimise CO, HC and NO_X emissions. For these to operate optimally, the devices must reach a temperature of around 350°C (The Open University, 2017) and this is unlikely in short trips. Therefore, they often do not operate in optimal conditions and emissions are not reduced as intended. Secondly, the driving cycle used for vehicle type approval (the New European Driving Cycle) is not representative of real driving conditions and under reports real-world driving conditions. Thirdly, companies such as Volkswagen have beaten the vehicle test emissions by developing algorithms that are capable of recognising that the vehicles are being tested and adjust emissions to unsustainably low levels. Both factors, have not helped to reduce air quality and GHG emissions. Thompson, Carder, Besch, Thiruvengadam, and Kappanna (2014) found out that the real-world emissions of NO_X of some models were 15 to 35 times higher than reported by the vehicle manufacturers.

There are many powertrain improvements that can contribute to increase energy efficiency and therefore mitigate emissions from cars. According to Cullen and Allwood (2010) the maximum efficiency of diesel cars is around 22% and 13% for petrol ones. Beyond this level, energy savings can only be obtained by decarbonising fuels or by improving other areas of the vehicles such as aerodynamics drag, reducing vehicle weight, lowering rolling resistance or by changing driving behaviour. In contrast, BEV and FCEV work with electric motors which are 93% efficient (Cullen & Allwood, 2010) and they do not emit pollution or GHG at their point of use. As a result, BEV and FCEV seem to be the only long-term realistic solution for meeting the mobility needs of society while allowing the Government to meet the signed international environmental agreements, such as the COP21.

2.1. Battery Electric Vehicles

According to EAFO (2017) 10,375 BEV were sold in the UK in 2016, almost half of them being Nissan Leaf, and almost a quarter Tesla. BEV are plug-in cars fitted with an electric motor powered by a large battery (Figure *3*). The battery is typically made of lithium-ion (Li-ion) and is recharged from the power grid. As electric motors are simpler than ICE and do not require gearboxes, BEV powertrains are typically cheaper and easier to maintain than conventional ones. However, the costs of batteries make these vehicles considerably more expensive at the moment.

Bloomberg estimates that BEV will reach parity with ICE vehicles by 2022 (Randall, 2016), a moment in which sales will lift-off.

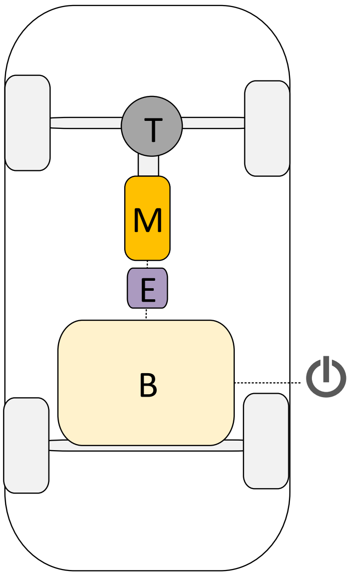

Figure 3. Schema of a BEV. Components: B-battery, E-electronic controllers, M-electric motor, T-Transmission.

A list of commercially available BEV has been compiled in Table *4*. The vehicles shown are 2017 models and their energy consumption is given according to the USA combined EPA driving cycle and according to the European NEDC. EPA is considered to provide more realistic fuel consumption figures and as this is the figure used when calculating several key performance indicators. This Table also indicates the size of the battery, which is a good proxy for vehicle range and recharging times using a domestic 7.4kW charger (230VAC/1P/32A), as this one is likely to be one of the most powerful that most customers may be able to install at home.

Table 4. List of BEV models commercially available in the USA in May 2017.

Brand	**Model**	**kW**	**Category**		**Vehicle Class**	**Price[3] (£)**	**EPA Range[4] (mi)**	**EPA MPG$_e$**	**NEDC Range[5] (mi)**	**Energy (kWh /100km)**	**Size battery (kWh)**	**Recharging Time (hrs)[6]**
BMW	i3 BEV/60A	125	M1	B	Subcompact Cars	31,440	81	124	125	27	33	2:59
BMW	i3 BEV/94A	125	M1	B	Subcompact Cars	32,330	114	118	195	27	33	4:29
Chevrolet	Bolt	150	M1	A	Small Station Wagons	30,238	238	119	323	28	60	8:09
Fiat	500e	83	M1	A	Minicompact Cars	25,645	84	112	87	30	24	3:15
Ford	Focus Electric	107	M1	C	Compact Cars	31,395	115	107	155	31	34	4:33
Hyundai	IONIQ Electric	88	M1	C	Midsize Cars	28,995	124	136	174	25	28	3:48
Kia	Soul EV	81	M1	B	Small Station Wagons	29,995	93	105	132	32	27	3:40
Mercedes	B250e	132	M1	M	Midsize Cars	34,580	87	84	124	40	28	3:48
Mitsubishi	i-MIEV ES	49	M1	A	Subcompact Cars	18,544	59	112	99	30	16	2:10
Nissan	LEAF S	80	M1	C	Midsize Cars	30,290	107	112	155	30	30	4:04
Smart	ForTwo	55	M1	A	Minicompact Cars	23,273	68	107	99	24	17	2:23
Volkswagen	e-Golf SE	100	M1	C	Midsize Cars	27,180	119	119	186	28	36	4:51
Tesla	Model S 75	193	M1	E	Large Cars	61,880	249	98	298	34	75	10:11
Tesla	Model X AWD 75D	193x2	M1	J	Standard Sport Utility Vehicle 4WD	75,400	238	93	259	36	75	10:11

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[3] Excluding subsidies.

[4] EPA combined driving cycle.

[5] NEDC driving cycle.

[6] Assuming a 7.4 kW (230VAC/32A) chargers for all BEV.

2.1.1. Electricity Production Pathways

Although BEV do not produce tailpipe emissions, well-to-tank emissions depend on how the electric power is generated. Figure *4* illustrates the carbon intensity of several electric pathways. The carbon footprint on the national grid varies for each country as each one has a different mix of energy sources. For example, in the UK, each kWh generated emits 459 gCO_2e (CCC, 2016b) due to the combination of fossil fuels and renewables in the energy mix. This value is expected to decrease to 81 gCO_2e by 2032 as stipulated in the cost-effective path of the 5th Carbon Budget (CCC, 2016b) and by 2050, it is feasible to reach 1 gCO_2e/kWh. This will be possible by using fossil fuels in a first stage in combination with carbon capture and storage and by fully deploying renewable capacity in the long term.

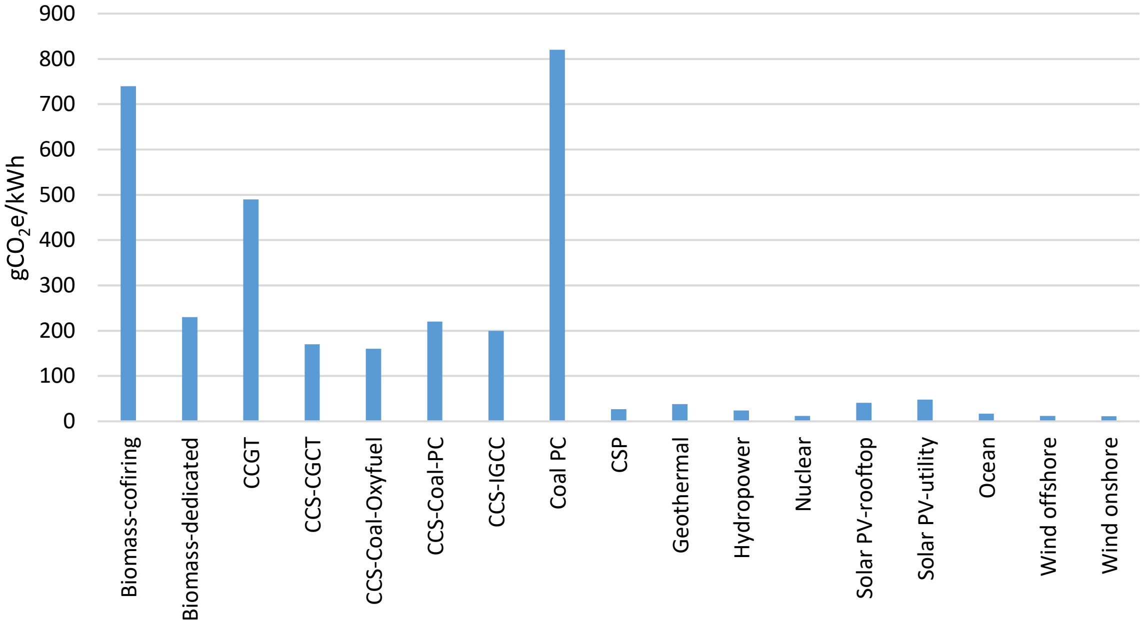

Figure 4. Carbon intensity of different power generation pathways. Source: Schlömer S. et al. (2014).

TTW emissions from electric cars are zero. However, due to the carbon intensity of the UK power grid, on a WTW basis, electric cars produce significant emissions (somewhat fewer than petrol and diesel cars), as Chapter 4 shows. By 2050, WTT emissions will be almost negligible, and the main emissions will be the result of vehicle manufacturing.

2.1.2. Batteries

The energy density of mineral petrol is 13,095 kWh/tonne[7] (9,572 kWh/m^3) and the one of diesel is 12,683 kWh/tonne (10,640 kWh/m^3) (Bader, 2016). In contrast, the energy density of Li-ion batteries is just around 90-175 kWh/tonne (200-350 kWh/m^3), as illustrated in Figure 5. This means that for a vehicle to reach a similar range to an ICEV, it requires a storage capacity that is around 100 times heavier and 50 times larger. As this is unfeasible, currently BEV have a much shorter range than conventional cars. A way to overcome this is by hybridising powertrains, this can be done by using an ICE to power the electric battery or adding a range extender (e.g. a small fuel cell system). As the ICE can work at its optimal engine map spot, the efficiency of the vehicle is slightly better. However, combining two energy systems increases complexity and unreliability and it is likely that hybrids could be leapfrogged by plug-in BEV (Goldman Sachs, 2016). Element Energy (2017) reports that in the next 10-15 years Li-ion battery technology will improve energy density, depth of discharge and thermal management, which will decrease costs and increase range. This research also supports this statement as a justification for considering just plug-in BEV.

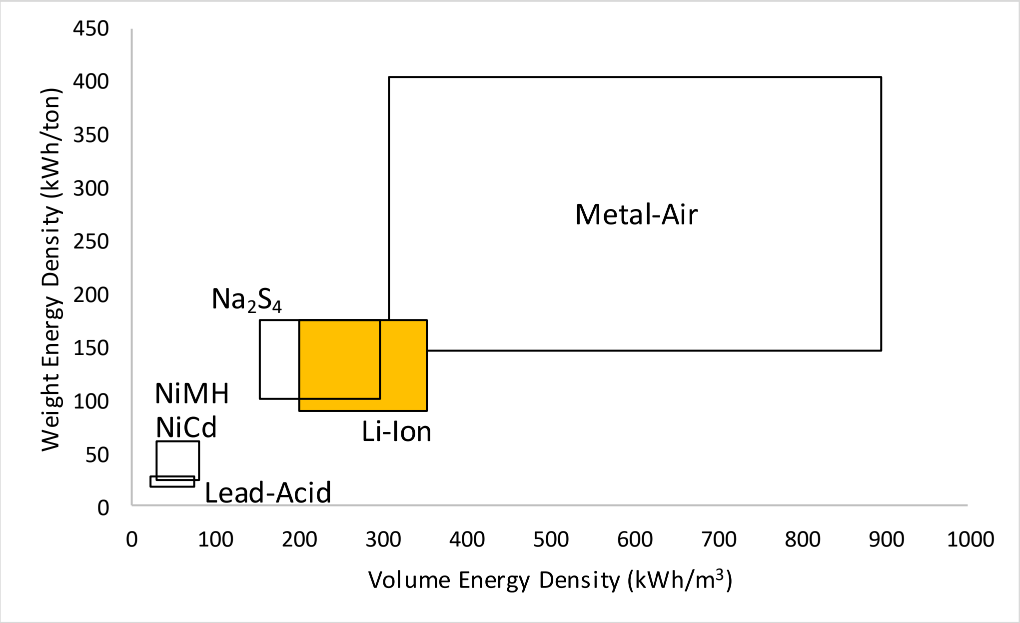

Figure 5. Energy density of batteries. Adapted from Berecibar and Zhou (2013).

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[7] High heating value (gross calorific value)

As batteries represent a third of the cost of BEV (Randall, 2016), economies of scale can decrease prices considerably and provide a competitive advantage to vehicle manufacturers. To this end, the industry is investing heavily is scaling up production from less than 30 GWh in 2016 to almost 190 GWh by 2020, enough capacity to power 2.6 M vehicles worldwide. As illustrated in Table *5*, most of the production will be located in China (64.5%), followed by the USA (20.4%) and Korea (12.4%).

Table 5. Main electric cars' battery manufacturers worldwide. a) Cell production; b) at 70 kWh/vehicle (in thousands by 2020). Adapted from Goldman Sachs (2015); Sanderson et al. (2017) and own research based on suppliers' commercial literature.

Company	Capacity (GWh in 2016)	Capacity[a] (GWh in 2020)	EVs equivalent capacity[b]	Location	Main customers
Boston Power	1	8	114	Liyang, China	Beijing Automotive Group, Saab
BYD	3	17	243	Shenzhen, China	BYD
CATL	5	50	714	Ningde, China	BMW, Saab, Volkswagen
Foxconn	0	15	214	Anhui, China (Shanxi)	BAIC Motor Corp
LG Chem	8	18	257	Ochang, S. Korea	GM, Renault, Hyundai, FOMOCO, Volvo, Volkswagen
	2	8	114	Nanjing, China	
	1	3	43	Michigan, US	
	0	5	71	Wroclaw, Poland	
Lishen	3	20	286	Tianjin, China	JAC
Panasonic / Tesla	3	35	500	Nevada, US	Tesla
Samsung SDI	3	5	71	Ulsan, S. Korea	BMW, Volkswagen, Fiat
	2	2	29	Xian, China	

Transitioning towards a world where all vehicles are electric might be constrained by the availability of raw materials. Furthermore, current batteries rely heavily on lithium (a limited resource) and 99% of the reserves are located in just four countries (Figure 6). This does not seem too sustainable in the long run and it does not seem to contribute to provide energy security, one of the reasons, aside of climate change, to move towards alternative energy sources.

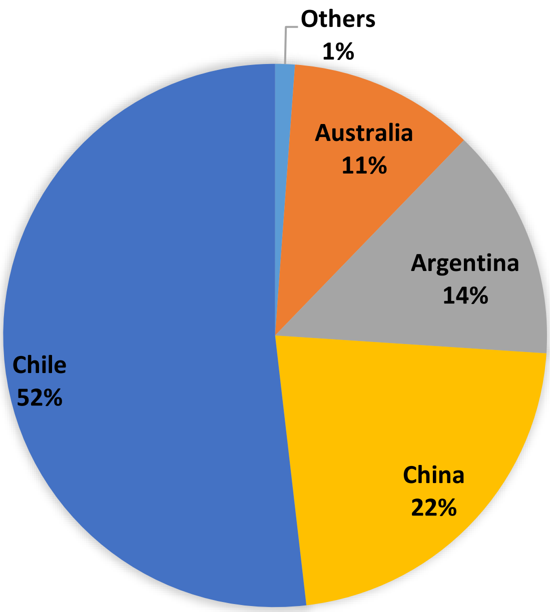

Figure 6. Location of lithium reserves worldwide. Adapted from: USGS (2017a).

2.1.3. Power Infrastructure & Chargers

The UK generated 273TWh of power in 2015 with an installed capacity of 68 GW (Figure *7*). The demand for electricity is expected to continue growing in the coming years and the fact that obsolete coal, gas and nuclear plants will be retired before 2030 means that, excluding demand from electric vehicles, there will be a deficit of 108 TWh and 191 TWh by 2025 and 2030, respectively (CCC, 2015).

Currently, BEV represent an almost negligible percentage of the UK vehicle stock. A future with higher penetration of electric cars will impose an even stronger pressure on the national grid generation and capacity. It is necessary to plan ahead and deploy the required infrastructure to enable electric cars to flourish. This could be possible only by installing new nuclear power stations and further renewables, if GHG are to be kept at the lowest possible levels, or deploying carbon capture and storage technologies (CCS). CCS have not been tested on a commercial and large scale yet and therefore it is unknown if this will be technically feasible. Besides, unless the prices of carbon emissions rise, it is also uneconomical. The cost of building nuclear power plants is very expensive and it takes several years to build them. Furthermore, after Fukushima, the public's views on nuclear power has become more negative. There is also the problem with the management of nuclear waste as several issues with Sellafield reported by the media show. In addition, once the UK has left the EU, it is unclear how this may affect the trade of nuclear fuels and critical parts. There is much hype regarding the deployment of renewables to provide low carbon electricity. However, due to the intermittency of generation, these must be coupled to energy storage technologies (e.g. batteries, hydrogen or pumped storage). As not every day is sunny and windy, deploying the additional capacity required to power all BEV would require to over compensate for these, and many of these plants would be idle for long periods of time (e.g. very windy days). As this would decrease their profitability, relying only on renewables does not seem a realistic solution.

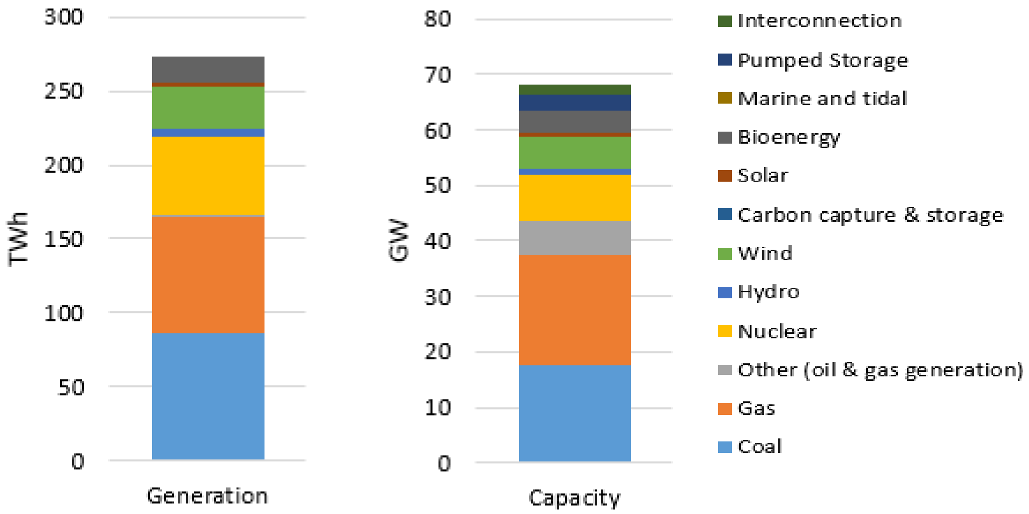

Figure 7. UK Power generation and capacity. Adapted from: CCC (2015).

BEV can be plugged onto the grid directly via vehicles' in-built chargers or via external chargers that are more powerful. Most cars include a 240VAC/3.6 kW on-board charger; however, this doubles the recharging time compared to the ones reported in Table *4*. This means that to fully charge a BEV, often requires to be connected to the power grid the whole night. Batteries produce DC power, and there are superchargers that can charge 80% of BEV batteries in less than half an hour. To install those, it is necessary that the cables that arrive to the recharging point have the right thermal resistance. This means that it is not possible to install superchargers everywhere without checking this with power distribution companies and often expensive infrastructure installation works will be necessary to adapt the low voltage network. The progression in recharging infrastructure in the UK is illustrated in Figure *8*.

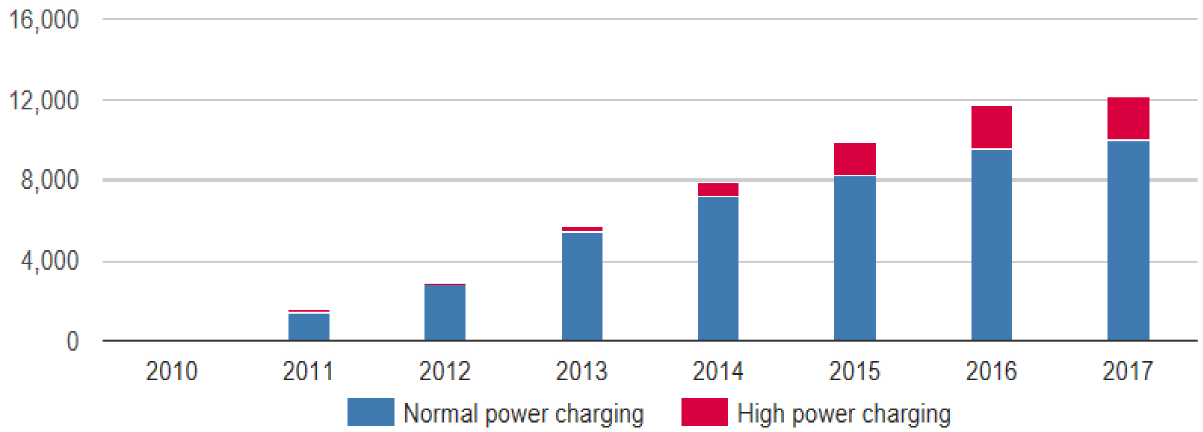

Figure 8. Recharging points in the UK. Source: EAFO (2017)

The Electrical Avenue Project analysed the impact of BEV on the low voltage network and rural electrical feeders in 10 different areas of the country. It was found that in 4 of these areas, the infrastructure should be improved in the next 15 years to enable penetration percentages of BEV between 30-80% (EA Technology & University of Manchester, 2015a) and in many other areas when reaching 100%. The project assumed slow charging modes, similar to the requirements of a Nissan Leaf (24 kWh, 3.6 kW power and absorbing reactive power), which means that with faster chargers (7.2 kW) the problem would present itself much sooner; and even more so if some consumers would install superchargers (e.g. 230VAC/43 kW). The reason is that peak demand can breach the thermal limit of cable feeders, more obviously on windier weekdays, and this requires the reinforcement of the network (this consists on replacing conductors). Even with algorithms, managing the demand-side response in some of these feeders, between 5-14% of customers would be affected daily, with all customers suffering charging delays for more than 3 hours several times a year. Nevertheless, these delays are unlikely to present a huge problem to most customers, as BEV could complete their recharging cycles if they are plugged in overnight. However, continuous switching of the chargers to balance the grid (and avoid flickering) is likely to affect battery life if the cycle times are under 2 minutes (ideally cycles should be 2-30 minutes) (EA Technology & University of Manchester, 2015b). Currently, due to the low uptake of BEV this is not a problem; however, in the long-term, this issue should be of interest to BEV manufacturers as this might decrease battery life (many manufacturers guarantee their batteries for 8 years or 100,000 km whichever is achieved soonest).

The impact of BEV on the grid will be significant and will require more intelligent cycling or charge management, supported by smart grids and demand side response policies. This is something that will interest local authorities as well, as these are responsible for granting rights to conduct works on public roads for network reinforcement, which could increase commuters’ travelling times if not managed properly.

To overcome the challenges regarding recharging times and poor infrastructure, companies such as TESLA are deploying their own. Tesla has deployed 120 kW chargers (instead of the basic 3.6 kW) that than can provide enough energy for 170 miles in just a half an hour charge. For example, it can charge 80% of a Tesla S with a 90 kWh battery in just 40 minutes (100% in 75 minutes) (Tesla, 2017). These ‘Superchargers’ are strategically located near congested city centres and busy motorways. There are currently 828 Supercharger Stations worldwide (37 in the UK), fitted with 5,339 superchargers. Before 2017, buyers enjoyed free recharging for life. This is not the case anymore. Nevertheless, Superchargers are a unique selling point for Tesla users and a competitive advantage of the company in respect to newcomers to the BEV space. For KPMG (2017), this demonstrates that an e-mobility strategy does not finish with the delivery of the vehicle to the customer but includes ‘servicing the customer over the whole lifecycle’. According to DeBord (2017), Tesla should deploy 30,160 Superchargers to provide similar usability to its cars. The infrastructure capable to provide superfast charging capabilities to the USA would cost to the company $7.5bn, and their technology is proprietary and Tesla vehicles plugs are not standard, they should invest by themselves, which seems unrealistic. Long recharging time is one of the key weaknesses of BEVs, and other manufacturers are also working on reducing this time with even larger superchargers. BMW, Mercedes, Ford and Volkswagen have created a joint venture to build 400 stations around the EU with chargers able to deliver up to 350 kW, as this would also allow longer distance travel, which in turn is likely to increase sales (Daimler, 2017). The cost of investment is typically so large that many automakers create strategic alliances to share the risks and standardise systems, as a way to benefit the whole sector competing against conventional vehicles. In addition to these alliances, BEV and FCEV automakers also acquire other companies to get the expertise that they lack. This is one of the basic abilities in managing innovation postulated by Bessant, Tidd, and Pavit (2005)[8].

2.2. Fuel Cell Vehicles

Currently, sales of FCEV are symbolic, due to mainly the lack of refuelling infrastructure. Just two vehicle manufacturers sell FCEV in the UK (Toyota and Hyundai, Figure *9*). In the USA, Honda also commercialises a FCEV model. As illustrated in Table *6*, the energy consumption of these models almost doubles the one of BEVs (Table *4*), and with exception of Tesla, their cost is also twice as expensive. Externally, FCEV are the same as counterfactual models; however, looking at the bonnet, the place used by the ICE is occupied by a fuel cell (Figure 10). As illustrated in Figure *11*, FCEV share some common technologies with BEV. Both have electric motors, transmissions, electronic controllers and batteries. However, batteries of FCEV are much smaller as they are only used to provide initial power to the motor as the time of reaction of the fuel cells is slower. New models suggested by Daimler, will have much larger batteries and they will be able to connect to the grid, in what constitutes a BEV-FCEV hybrid de-facto. The fuel cell is responsible to provide the energy required by the electric motor. Fuel cells are electrochemical devices that convert a chemical energy (e.g. hydrogen) into electricity. FCEV fill their tanks in refuelling stations with hydrogen typically at 70 MPa, in a similar way and time as conventional cars do.

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[8] Others include recognizing signals from the environment to trigger the process of change, aligning business strategy with the required changes, generating internal R&D, choosing the right responses , managing the lifecycle of the innovation, implementing changes, learning and identify lessons for improvement of management and finally, developing the organisation in a way that effective routines are embedded within the organisation.

Figure 9. FCEV commercialised in the UK in 2017. Left, Toyota Mirai. Right, Hyundai ix35.

Figure 10. Front view of a FCEV, where the FC is in the middle

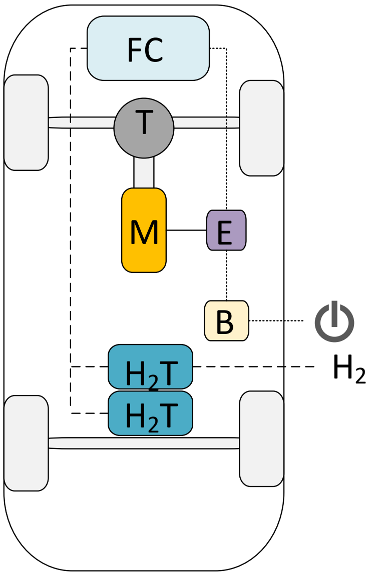

Figure 11. Schema of a FCEV. Components: B-battery, E-electronic controllers, M-electric motor, T-Transmission, H2T-hydrogen tank, FC-fuel cell.

Table 6. List of FCEV models commercially available in the USA in May 2017.

Brand	**Model**	**kW**	**Category**	**Vehicle Class**	**Price[9] (£)**	**EPA Range[10] (mi)**	**EPA MPG$_e$**	**NEDC Range [11] (mi)**	**Energy (kWh /100 mi)**	**Size H_2 tank (kWh)**	**Refuelling Time (h:min)**
Honda	Clarity FC	130	D	Midsize Car	*67,849*	366	67	434	59	188	00:04
Hyundai	ix35	100	J	Small SUV	57,605	265	49	369	81	187	00:04
Toyota	Mirai	113	D	Subcompact Car	66,000	312	66	342	60	167	00:03

2.2.1. Hydrogen Production Pathways

At present, the chemical industry accounts for 93% of all hydrogen consumption worldwide (Figure 12). Hydrogen is used in the production of ammonia (53% of the total) mainly for nitrogen fertilizers, as well as in methanol synthesis (7%), with smaller quantities used in the production of polymers and resins. These industries primarily use steam reforming of natural gas (SMR) where possible, or coal or oil gasification in locations lacking a supply of natural gas. The oil industry uses hydrogen for refining crude oil via hydrocracking and hydrotreating, and to eliminate

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[9] Excluding subsidies.

[10] EPA combined driving cycle.

[11] NEDC driving cycle.

sulphur from transportation fuels to meet Fuel Quality Directives. All of these industries require gaseous hydrogen and can use relatively impure hydrogen, which is mostly derived from fossil fuels (Figure 13) as these have the lowest costs (P. E. Dodds, 2015).

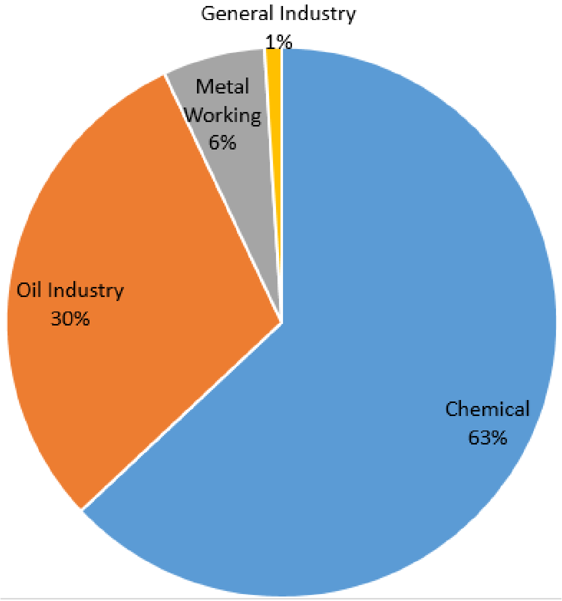

Figure 12. Consumption of Hydrogen worldwide. Adapted from Fraile (2015).

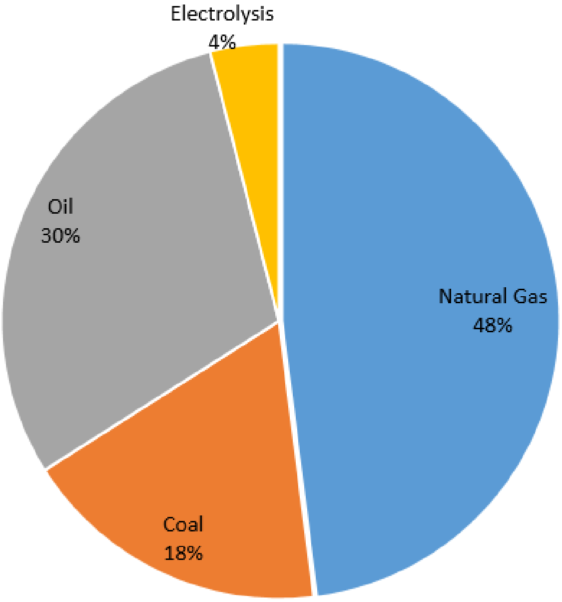

Figure 13. Main feedstocks in hydrogen production. Adapted from Hornung (2014).

Transport is potentially the principal market for hydrogen in the future (Automotive Council UK, 2013; Paul E. Dodds & Ekins, 2014; Paul E. Dodds & McDowall, 2014; King, 2007b). Hydrogen is a carrier rather than a fuel, as it is not found in its pure form anywhere on the planet and it requires conversion from a primary energy source. As a result, it releases less energy than the energy required to produce it. As hydrogen has an energy density of 141 MJ/kg H_2, one kg contains the equivalent of 1 gallon of petrol. Hydrogen for transportation could have a significant impact on the hydrogen market; however, it requires a purity level of 99.9999%, way beyond the level required in industrial processes or heating, as this avoids the catalyst poisoning of the most common type of fuel cell fitted in cars (proton exchange fuel cell). This can be achieved via electrolysis or by fitting air filters in other less clean production processes; however, this is an energy intensive process that reduces the efficiency even further. Some hydrogen production pathways can use fossil fuels while releasing low GHG emissions when CO_2 is captured in CCS plants. Hydrogen can be produced from a very broad range of pathways (Table 7), including renewables and biological pathways; however, some of these present a low technological readiness level and in some cases poor energy efficiency.

Table 7. Efficiency of different hydrogen production pathways. Source: Velazquez Abad and Dodds (2017).

Production Technology	**Main Feedstocks**	**System Energy Efficiency[a] (%)**		**USA H_2 Cost[b] ($/kg)**		**Maturity Level[c]**
		2015	**2020**	**2015**	**2020**	
Reforming: Steam Methane	Natural Gas + steam	74%	≥74%	2.1	≤2.1	Commercial
Gasification: Biomass	Biomass	46%	48%	2.1	2.0	Pilot Projects
Electrolysis: Alkaline	Water + electricity	73%[d] 72%[e]	75%[d] 75%[e]	3.0[d] 3.9[e]	2.0[d] 2.3[e]	Commercial
Water Splitting: Solar Thermo-chemical	Water + sunlight	10%[f]	20%[f]	14.8 [f]	3.7 [f]	Pilot Projects
Biological: Photolysis (Photosynthesis)	Water + Sunlight	2%[f]	5%[f]	N/A	9.2 [f]	Pilot Projects
Biological: Dark fermentation	Biomass	4 mol H_2 / mol glucose	6 mol H_2 / mol glucose	N/A	N/A	Research Lab
Biological: Photo fermentation	Biomass + sunlight	0.1%	N/A	N/A	N/A	Research Lab

a) LHV; b) Estimated hydrogen levelised cost in the USA; c) As per November 2016; d) Central production; e) Distributed production; f) Solar-to-hydrogen ratio; defined as the energy of the net hydrogen produced divided by net full spectrum solar energy consumed.

FCEV do not produce carbon emissions at the point of consumption; however, depending on how the hydrogen is produced, well-to-tank (WTT) emissions can be even higher than conventional fuels. Figure *14* and Figure *15* illustrates that there are many conventional pathways that despite using similar technologies (e.g. electrolysis of thermal processes), carbon intensities at the point of production (PoP) and at the point of use (PoU), vary greatly. In contrast, using UK emission factors for company reporting from Bader (2016), a kWh of petrol and diesel generate WTT emissions of 47.05 and 51.94 gCO$_2$e[12], respectively. Edwards, Larive, Rickheard, and Weindorf (2014) estimated this to be around 43.9-55 gCO$_2$e/kWh and 49.7-61.2

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[12] HHV (gross calorific value), 100% mineral origin.

gCO₂e/kWh for diesel. This indicates that in order to contribute to reduce GHG emissions, wind power (WDEL1) is the best way forward to generate hydrogen via electrolysis and farmed (WFLH) or wasted wood (WWCH) gasification when following thermal processes. One of the key selling points of FCEV is that they do not produce tank-to-wheel (TTW) GHG emissions; however, climate change is a global issue and where carbon emissions are produced along the supply chain is irrelevant; it is important to avoid these as much as possible, and this is something that hydrogen can deliver when it is produced from renewables or biomass gasification.

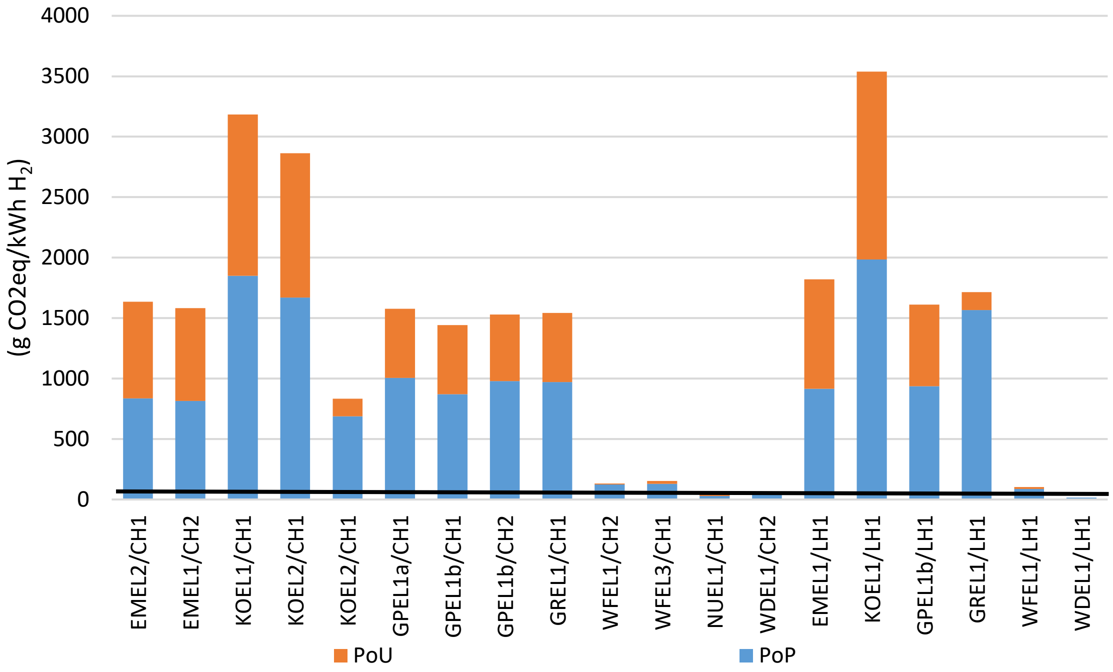

Figure 14. Carbon intensity electrolytic hydrogen production pathways. PoP: Point of production. PoU: Point of use (conditioning and distribution emissions).Adapted from: Edwards et al. (2014).

Hydrogen is an ideal ‘fuel’ for oil companies, as it can facilitate their transition towards a lower carbon future. Hydrogen and fossil fuel supply chains share much in common, including synergies in production, but also transportation, distribution and end use (Scottish Government, 2017). In production, hydrogen is already used by oil

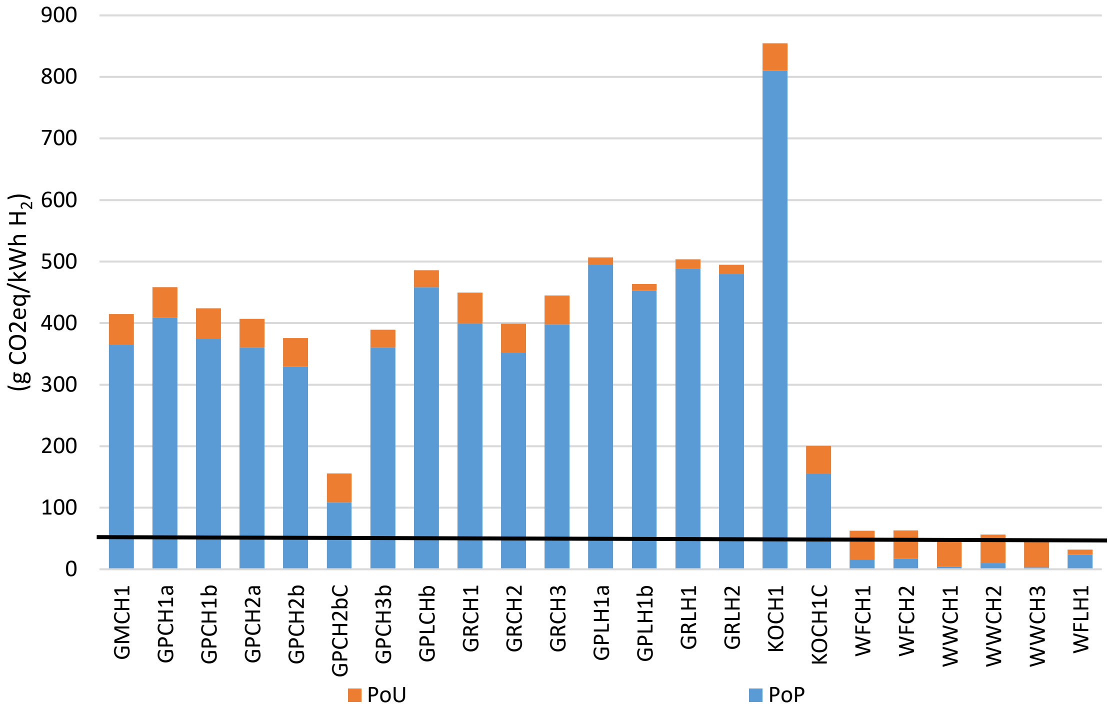

Figure 15. Carbon intensity thermal hydrogen production pathways. PoP: Point of production. PoU: Point of use (conditioning and distribution emissions). Adapted from: Edwards et al. (2014)

companies to improve the quality of fuels and some of the production methods of oil share technologies with steam reforming or gasification. Furthermore, hydrogen could be stored in salt domes and likely depleted oil fields. Hydrogen is a gas, and as such, it is typically compressed and transported via pipelines or by road in trucks with high compressed tanks or liquefied in cryogenic tanks. This is also similar to the distribution chain already managed by oil companies. Transporting liquefied hydrogen is slightly more complex, as it has a boiling point that requires venting some of the hydrogen on a daily basis. Nevertheless, there is much interest on developing liquid hydrogen tanker ships (similar to liquid natural gas ones). Kawasaki is designing a liquid hydrogen carrier (up to ~260,000m^3) to transport hydrogen produced from brown coal from Australia to Japan (KHI, 2016). According to FCH JU (2012), liquid transport is cheaper for distances over 275km (at a cost between €1.7-2.2/kg H_2[13]), and 50MPa tanker trucks for shorter distances (at a cost between €1 -1.7/kg H_2). In contrast, the cost of pipelines can quickly escalate to

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[13] 1 GBP = 1.15 EUR

€3.64/kg H_2). Paul E. Dodds and Demoullin (2013); Paul E. Dodds and McDowall (2013) suggest that adapting the natural gas grid to transport hydrogen could be a cost effective solution for decarbonizing the heating system. If so, the same pipelines could transport hydrogen used in transportation at a fraction of the cost. Other transportation methods exist via liquid hydrogen organic carriers (Preuster, Papp, & Wasserscheid, 2017) or other carriers such ammonia (Little, Smith, & Hamann, 2015). However, this would require another conversion step, which would reduce the overall energy balance.

Most automotive executives (78%) believe that FCEV will solve the recharging and infrastructure challenges that BEV present and consider FCEV as the ‘real breakthrough for electric mobility’ (KPMG, 2017). They consider that it is not reasonable to wait for 24-45 minutes to recharge a battery. FCEV present a similar customer experience to conventional cars: the users go to the refuelling station and refill the hydrogen tank in under 5 minutes. For all these reasons, and despite marginal sales of FCEV, there is much interest in industry to develop and commercialise this technology. Recently, 13 global leader organisations including several manufacturers from the transport sector (Alstom, BMW, Daimler, Honda, Hyundai, Kawasaki and Toyota), oil and energy companies (AngloAmerican, Engie, Shell and Total) and gas suppliers (Air Liquide, The Linde Group) have created the Hydrogen Council. Its members are committed to promote hydrogen and fuel cells to meet the 2°C target agreed in the UNFCCC (2015) by investing £1.2 bn/year (Hydrogen Council, 2017). Nevertheless, one of the key weaknesses of FCEV is the lack of infrastructure. As suggested by Velazquez Abad (2010), there is a chicken and egg circle where customers do not want to buy FCEV due to poor infrastructure, and investors do not want to in deploying refuelling stations due to poor vehicle sales. One of the effective ways of breaking this cycle is by dedicating public funding at the initial commercialisation stages. However, the commitment has been much stronger in other countries; while there are 14 hydrogen refuelling stations (HRS) in the UK now and not a Governmental target for the near future, in other countries such as Germany, the Government is going to deploy 400 HRS by 2023, Japan 420 by 2025 and South Korea 520 by 2030 (Velazquez Abad, 2017).

2.2.2. Fuel Cells

All FCEV commercialised in 2017 are fitted with a proton exchange membrane fuel cell (PEMFC); however, this is not the only alternative. Nissan is working on a solid oxide fuel cell (SOFC) powered by bio-ethanol but this is just a demonstration vehicle at the moment (Nissan, 2016). For this reason, this study assumes that all FCEV are built with PEMFC. These devices can convert hydrogen into an electrical current that power an electrical motor. As presented in Figure *16*, despite discrepancies in the number of transportation FC shipped in the past years, both sources agree that sales have grown from 2,000 in 2012 to more than 5,000 in just 3 years.

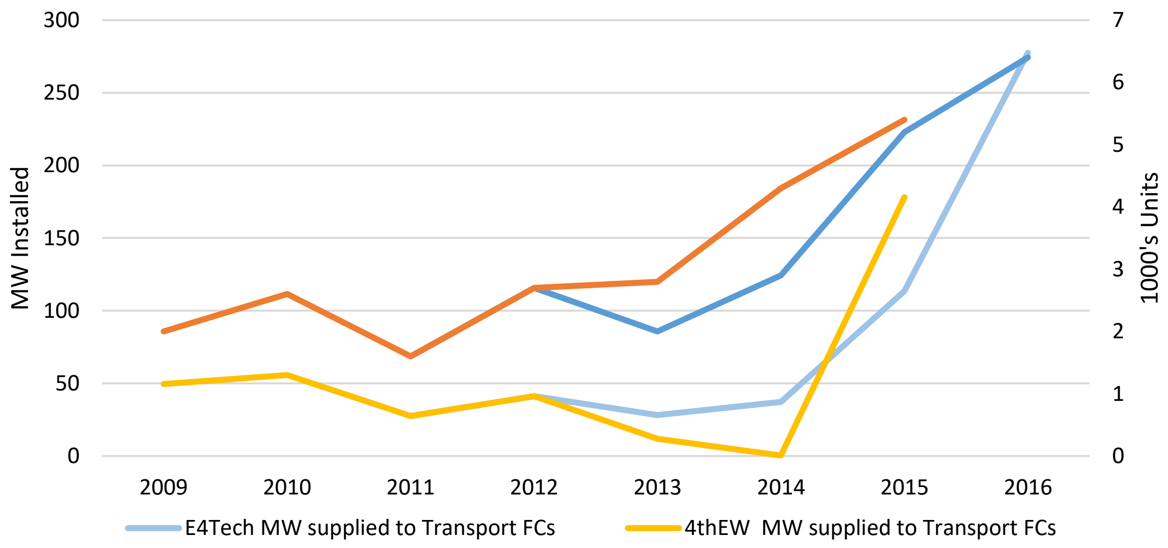

Figure 16. Shipments of Fuel Cells for Transportation. This includes all transportation modes. Adapted from Hart, Lehner, Rose, and Lewis (2016) and Adamson (2016).

Typically, platinum is used as a catalyst in fuel cells to facilitate the chemical reaction that produces electricity (and water as a by-product) from hydrogen stored in the tank and oxygen from the air. Platinum is an expensive metal with a price around £770/kg[14] (LME, 2017). Most platinum group metals reserves are located in South Africa (Figure *17*) which is not ideal to guarantee energy security. For both reasons, much research is being conducted to find cheaper and more abundant platinum-group metals (PGM)-free catalyst designs (FCH JU, 2016; US DoE, 2017a).

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[14] Price on 12th April 2017.

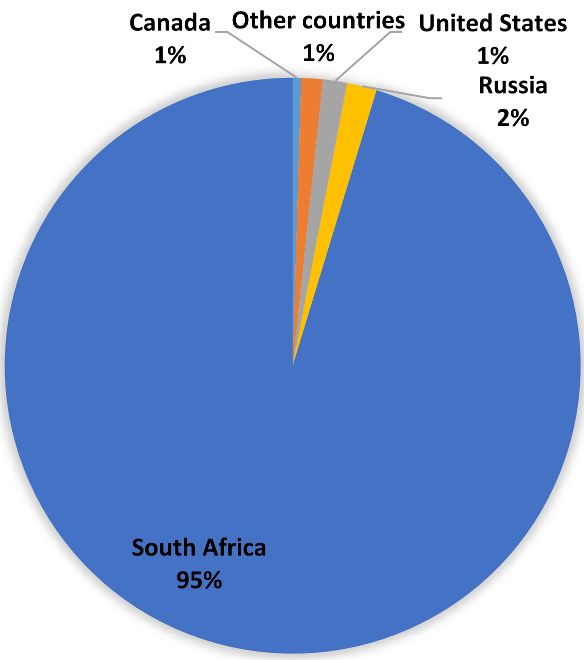

Figure 17. Location of platinum group metals reserves. Adapted from USGS (2017b).

2.3. Comparison between BEV and FCEV future costs

The success of BEV depends greatly on innovation in the area of batteries. Average battery pack prices fell from $1000/kWh in 2010 to around $227 in 2016 (Knupfer et al., 2017). Slowik, Pavlekno, and Lutsey (2016) suggest that currently battery costs can decrease to $145/kWh for production levels over 500k units (based on Panasonic-type 18650). Element Energy (2017) estimated that battery costs could decrease to $190 kWh by 2020. ARF and McKinsey & Company (2014) forecasted $127/kWh by 2025. However, the pace of product innovation has been much faster than expected and now Tesla and GM believe that its batteries will cost $100/kWh by 2020 (Element Energy, 2017; OECD/IEA, 2016; Slowik et al., 2016).

In contrast, the cost of FCEV depends on the cost of FC systems and hydrogen tanks. Estimations from Element Energy (2017) indicate that FC system costs could decrease to under £40/kW by 2030, and the cost of hydrogen tanks to around £12/kWh. FCH JU (2012) expects a decrease on fuel cell stack costs of 74% by 2030, to around £28.8/kW. The US DoE (2016), estimates current costs at around £43/kW, and it expects the costs to go down to £32.5/kW by 2020[15]. The Coalition

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[15] 1 GBP = 1.23 USD

(2010) expects the costs of FC systems to fall by 90% and BEV components by 80% by 2020.

Despite a massive price differential between BEV and FCEV in 2017, it is expected to decrease to around £650-£2,885 in favour of BEV by 2030 (Table *8*). However, by 2050, the difference will have almost disappeared, with some sources forecasting FCEV will be cheaper than BEV (Figure 18). For achieving such cost reductions, the literature assumes that the volume of BEV and FCEV penetration will reach 25% of overall cars or more. This will drive economies of scale and learning rates that will contribute to decrease fuel cell stack and battery costs. The Coalition (2010) assumes that FCEV will be cheaper than petrol ICEV cars if fossil fuel prices increase by 25% and learning rates after 2020 reach 15% or for very small price increases when learning rates reach 50%.

Table 8. Forecasted total costs of ownership of different vehicle types in 2030 and 2050 in GBP (1 GBP=1.15 EUR=1.23 USD). Adapted from 1. Körner, Tam, Bennett, and Gagné (2015) (BEV range = 150 km). 2.E4tech and Element Energy (2016). 3.Element Energy (2016).

Source \ Type of vehicle	**1 (2030)**	**1 (2050)**	**2 (2030)**	**3 (2030)**	**4 [16] (2050)**	**5 (2030)**	**5 (2050)**
ICE petrol	22,845	23,902	-	21,593	-	27,365	27,876
ICE Diesel	23,414	24,471	£28,800	21,188	£61,000	27,873	27,114
BEV	24,227	25,447	-	21,907	£54,000	30,161	27,368
FCEV	24,878	24,634	£31,200	24,792	£51,000	30,924	27,789

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[16] At 2012 values, applying an energy systems approach.

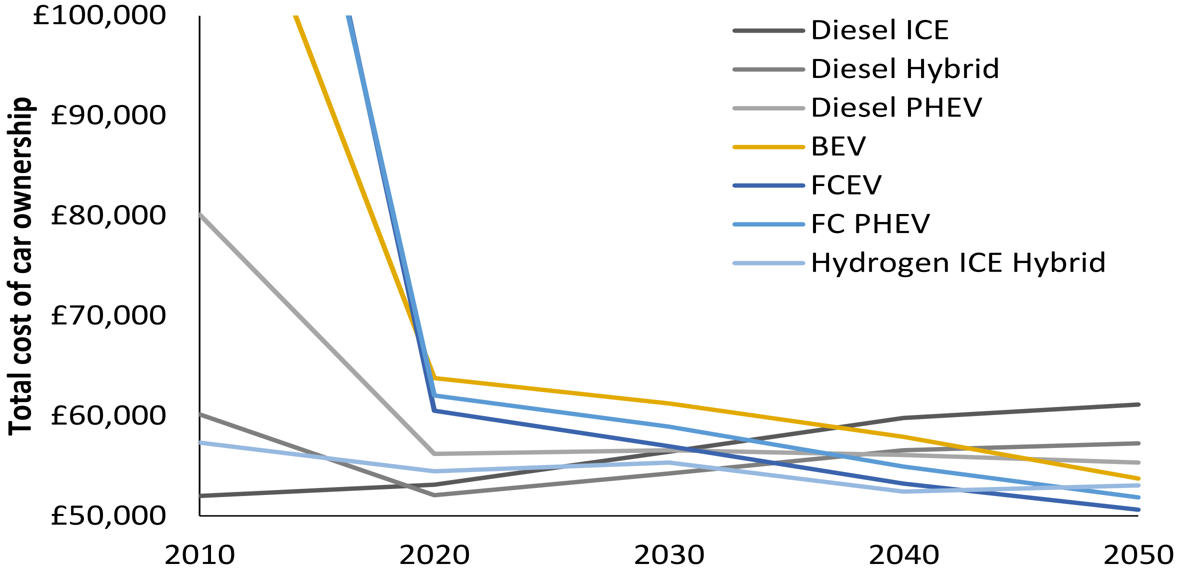

Figure 18. Total cost of ownership (TCO) for principal powertrains using the energy systems method, for the scenario with an 80% reduction in CO_2 emissions in 2050 relative to 1990. Source: Paul E. Dodds and Ekins (2014).

3. Literature Review

This Chapter introduces the academic literature in the areas of business strategy, innovation and g change management and it applies their main concepts and models to the context introduced in Chapter 2 (electric vehicles).

3.1. Strategy

In this section, the concept of strategy is introduced. The main strategic tools and frameworks from the 'business strategy' literature are presented and some implemented taking as example the electric automobile sector[17]. One of the most influential authors in the literature is Michael Porter. Porter (1996) understands strategy as the 'creation of a unique and valuable proposition, involving a different set of activities'. For Johnson, Whittington, and Scholes (2011) strategy 'is the long-term direction of an organisation'. They differentiate three levels of strategy. Corporate-level strategy is about the general scope of the firm and how adding value. Business-level strategy is concerned about how the business should compete in its market (also known as competitive strategy). Operational strategies look at how the different parts of a firm contribute to delivering the corporate and business-level strategies 'in terms of resources, processes and people'.

Mintzberg, Lamper, Quinn, and Ghoshal (2003) define strategy as 'the pattern or plan that integrates an organisation's major goals, policies, and action sequences into a cohesive whole'. It helps to manage resources into a 'unique' and 'viable posture' based on internal competencies (for this an analysis of strengths and weaknesses, might be useful) and changes in the environment (for this an analysis of opportunities and threats, as well as, a PESTLE analysis might be valuable).

One of the first activities that a firm must consider is identify its business units, divisions or market segments and the strategies of each one of these to provide goods or services to the external markets in which they operate. To succeed these must achieve a competitive advantage by creating higher value than the competition. Porter (1990) suggested that this can be done by being cheaper or more differentiated than rivals and identified three main strategies, according to the focus

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[17] Electric vehicles include battery and fuel cell electric vehicles.

on the competitive scope (whether the company serves all potential customers of focuses on a narrow segment of the market). This positioning has been applied to several of the automakers commercialising BEV and FCEV in Appendix II (*Figure 31*).

For Porter (1996), the essence of strategy is differentiation. As rivals can imitate improvements in quality and efficiency, choosing to perform activities differently from the completion makes more difficult for them to copy strategic positioning. If that difference can be sustained over time, the company can outperform rivals. Three sources contribute to the strategic position: serving few needs of many customers[18] (e.g. battery and fuel cell manufacturers); serving more needs of few customers[19] (e.g. Honda offers lifecycle management of FCEV); or serving broad needs of many customers in a narrow market[20] (e.g. Tesla sells cars and provides different types of services in selected markets). Porter also argues that strategies require to choose between trade-offs when competing and this implicates creating a fit between companies activities that can reinforce each other.

Ansoff (1988) identified four basic strategic directions for corporate strategy: market penetration, market development, product development and diversification. Typically, companies manufacturing electric vehicles diversify by producing new products but supplying the same market. In contrast, those same organisations, when dealing with conventional cars they seek market penetration (increasing market share). This implies greater economies of scale and faster learning curves, leading to greater bargaining power with suppliers (in relation to the Five Forces). Product development may require new strategic capabilities (e.g. new production processes or technologies) which tends to be capital intensive.

Porter (2008) developed a model to help companies to understand the structure of their industries and the areas that are more profitable and less likely to suffer attacks from the competition (this model is popularly known as Porter's Five Forces). The model looks at the competitive forces that can impact prospective profits. Companies must be aware of what their rivals are doing, but also they must recognise the negotiating power of their customers and suppliers, as well as, the effects that new

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[18] Also known as variety-based positioning
[19] Also known as needs-based positioning
[20] Also known as access-based positioning

entrants in the marketplace may have and substitute offerings that can decrease sales. The general application of this model for electric vehicle manufacturers is illustrated in Appendix III (*Figure 32*). Porter (2008) recommends to position the company where those forces are weakest. He also endorses reshaping the forces in favour of the company by using tactics aiming at capturing a larger share of the profits, such as:

- Use standards, as this makes easier to switch to other suppliers (therefore reducing the bargaining power of the suppliers). For example standardizing BEV connection plugs.
- Expand services to increase the switching costs of the buyers (hence reducing the bargaining power of customers). Examples of this include the Supercharger stations deployed by Tesla and the free refuelling costs for FCEV buyers offered in the USA by Honda.
- Neutralise competition by investing in offering differentiation to avoid price wars. Now, there is enough growth potential for all but there is not much competition because production levels are rather low.
- Impose high barriers of entry by investing in R&D and by achieving economies of scale that may increase the fix costs of competing
- Limit the threat of substitutes by offering better value. BEV and FCEV are not substitutes for ICE vehicles at the moment but they are substitutes between themselves.

Porter (1985) value chain describes the categories of activities which create a product or service. This model provides a tool for exposing the sources of competitive advantage and ‘the role of competitive scope in gaining competitive advantage’ (Porter, 1990). The model helps managers to consider the activities that contribute to create value. In this model (*Figure 19*), primary activities relate to the creation and delivery of a product or service and supporting activities improve the effectiveness and efficiency of these. This model is specific to each company as they have different production, market, and supply chain structures and they belong to their own particular value network. A value chain analysis is critical for BEV and FCEV automakers because new technologies require different supply chains. ICE are replaced by electric motors; fuel tanks for hydrogen tanks; small lead acid batteries by large lithium-ion ones. In addition, human resources have to provide a workforce with a different set of technical skills (more electro-mechanical). Technology development regarding batteries and fuel cells R&D and substitution of some critical raw materials (e.g. as catalysts) can contribute to create value. Simpler powertrain systems with fewer parts reduce the complexity of the procurement activity and it can even reshape the infrastructure of the firm. Fewer Kanban are likely to be necessary (thus reducing the blueprint of the production area) and just-in-time deliveries may become more fluid (which might decrease storage space needs).

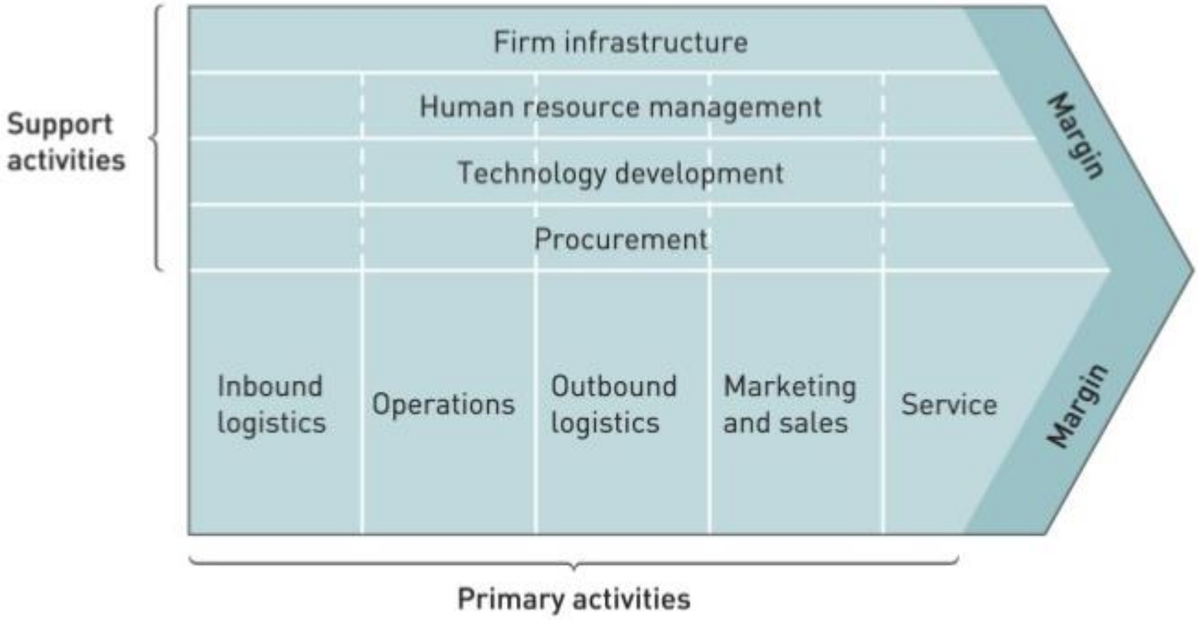


Figure 19. The value chain within an organisation. Source: Bessant and Tidd (2011). Adapted from Porter (1985).

Viguerie, Smit, and Baghai (2008) measure strategies temporarily following their ‘tree horizons framework’. Horizon 1 focuses on the immediate core activities, those that account for most profits and cash flow. In the context of the automotive industry, this relates to the current business model with conventional powertrains. These businesses need defending but the expectation is that there will be a long-term decline in profitability. Horizon 2 focuses on emerging business opportunities that one day may lead to new profitability streams that may become the core business of the future organisation.

SWOT analyses are expected to be summaries and prioritising the most relevant aspects that may affect the competitive position of a business. It looks at internal capabilities and the external environment that impact strategic development (Bessant & Tidd, 2011). Strengths and weaknesses provide an insight into the strategic capabilities of the firm. Understanding opportunities and threats is fundamental to evaluate strategic future choices by taking advantages of opportunities and responding strategically to mitigate any threats. BEV and FCEV are electric vehicles with motors that share much technology, as illustrated in Figure 3 and Figure 11. An exhaustive SWOT analysis for the electric vehicle industry has been included in Appendix IV (*Table 21*). Similarly, Appendix V (Table *22*) and Appendix VI (*Table 23*), illustrate SWOT analyses more specific to BEV and FCEV automakers, respectively.

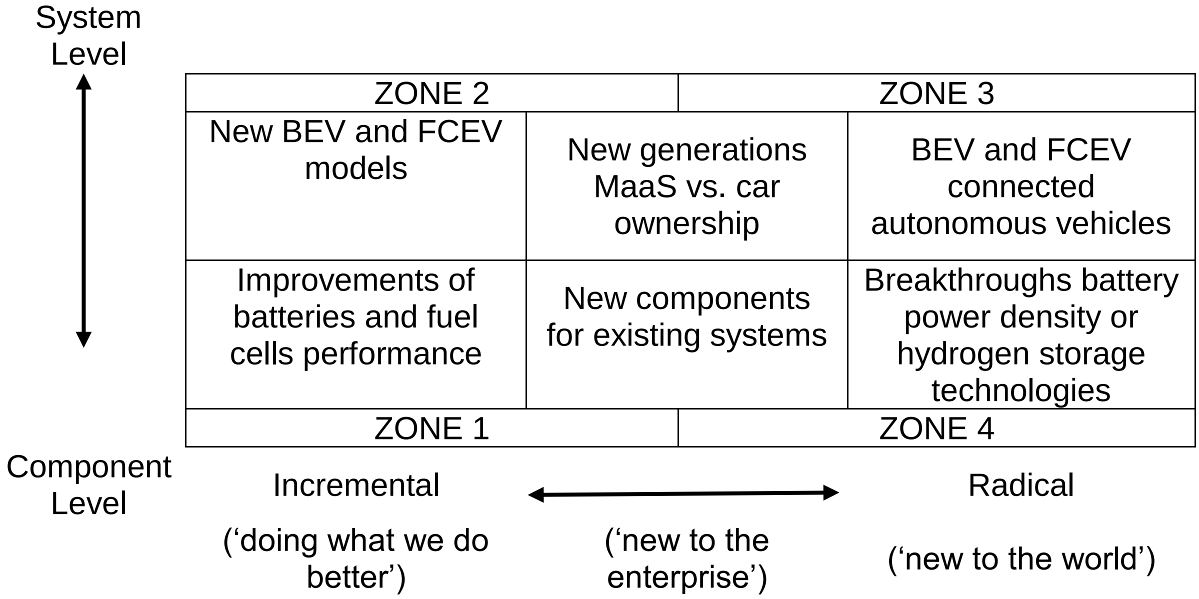
A PESTLE framework classifies the external environment in which organisations operate in six main influences (political, economic, social, technological, environmental and legal) that have an impact on the possible success or failure of particular strategies (Bessant & Tidd, 2011). A PESTLE analysis can reveal threats and opportunities derived from technological changes that can be fed into a SWOT analysis. A PESTLE analysis applied to the electric vehicle sector is illustrated in Appendix VII (The political and legal environment, for example, can help companies to identify future market changes. BEV and FCEV compete with a consolidated incumbent technology (ICEV) that provide longer range, convenient and widely available refuelling infrastructure, with well-developed supply chains and at a much cheaper TCO. A limited view would suggest that investing on electric powertrain vehicles is not a wise strategy. However, due to policy and societal changes, dependence on ICE sales could become a liability in the near future as many cities around the world are planning to ban polluting vehicles. As a result, there is an opportunity for conventional vehicle manufacturers to adapt and for new entrants to position themselves in this space.
Table 24).

3.2. Innovation

Innovation has been defined in many different ways.   For Drucker (1985), innovation is the tool that entrepreneurs use to exploit change as a new business opportunity. Porter (1990) indicates that companies achieve competitive advantage by innovating in the broadest sense, including technologies and ‘new ways of doing things’. Ian Miles, Paul Cunningham, Deborah Cox, Christina Crowe, and Khaleel Malik (2006) estate that an idea or project is innovative when it is applied in processes put onto the market or used in the public sector. Bessant and Tidd (2011) define innovation as the ‘core renewal process within an organisation, refreshing what it offers to the world and how it creates and delivers that offering’. For an invention to become successful it requires good targeting and positioning, distribution, advertising, promotion and pricing strategies, good organisational structures and good decision making approaches (Bessant & Tidd, 2011). Baregheh, Rowley, and Sambrook (2009) showed that just 5 out of 60 journal papers focused on the area of innovation, mentioned success as a pre-requisite. What seems universally accepted is that innovation is a necessary function to enhance strategic advantage (Schumpeter, 1950; Tushman, 1997) and as such, a precursor for economic growth and success (Baregheh et al., 2009; Bessant & Tidd, 2011; Porter, 1990). Companies seek to innovate to earn what Schumpeter (1950) calls ‘monopoly profits’. By doing so, they create a new competitive environment, and other companies react by innovating themselves trying to obtain a similar competitive advantage. Schumpeter (1950) called this constant search for innovation that destroys ‘old’ rules ‘creative destruction’.

In essence, condensing the different interpretations found in the literature, innovation consists in providing something new to the market (it can be a product, service, process) or something that adds value to a business, yielding a competitive advantage compared to the incumbent situation and it encompasses a broad spectrum of factors that include inventions, and often changes in attitudes, structures and processes within organisations.

When the linkages between core concepts and components are changed, innovation is radical and establishes a new dominant design linked to a new architecture. When these remain unchanged, innovation is incremental and improvements occur in individual components while the main architecture remains the same (Henderson & Clark, 1990). Similarly, Bessant and Tidd (2011) defend that incremental innovation originates from something that is known; while radical innovation involves a large deal of uncertainty (Bessant & Tidd, 2011). *Figure 20* represents these ideas applied to the electric car sector. As illustrated, radical innovation consists of overturned core concepts, where the linkages between components and systems are changed. Connected autonomous vehicles could be classified within this quadrant. Those epitomise the technology fusion between electric vehicles, computers and industrial controls, IT and infotainment, industrial automatisation, robotics, artificial vision and GPS. Managing innovation in zone 1 is easier because it is about steady-state improvements to products or processes and uses existing knowledge about the core component. This is typical of improvements of performance of well-known components such as batteries or fuel cells. In zone 2 new architectures emerge, often due to the different needs of consumers, that require the reconfiguration of existing knowledge in new ways or combining a mix of old and new. In zone 3 there is a discontinuous innovation that change the rules of the game where there is uncertainty in regards to the outcomes and there is scope for new entrants. In zone 4 there is a substantial change in some core components but there is no change at system level. It is necessary to acquire new knowledge but within the boundaries of well-known frameworks. Therefore, there is no need for major shifts or dislocations. For example, developing a new battery chemistry or fuel cell technology type that overcomes current challenges.



ZONE 2		ZONE 3
New BEV and FCEV models	New generations MaaS vs. car ownership	BEV and FCEV connected autonomous vehicles
Improvements of batteries and fuel cells performance	New components for existing systems	Breakthroughs battery power density or hydrogen storage technologies
ZONE 1		ZONE 4

Figure 20. Dimensions of innovation. Adapted from Bessant and Tidd (2011), Henderson and Clark (1990).

Porter (1990) highlights some basic principles that governments should embrace to stimulate innovation to gain a competitive advantage. One of these is focusing on 'specialised factor creation' and recommends Governments to focus (among other factors) on developing mechanisms such as research efforts in universities connected with industry. This seems to be one of the approaches taken by the UK Government. The BEIS and the automotive industry set up the Advance Propulsion

Centre (APC) in 2013 whose aim is to fund projects centred on low carbon technologies and reducing air quality emissions and it is one of the pillars of the new UK Industrial Strategy (APC UK, 2016). The APC is managed by the University of Warwick and it counts with many industrial partners. For the UK Government, innovation is disruptive and creates new things – products, processes, services and industries (Innovate UK, 2016). Since 2007, the UK invested £1.8bn in innovation, and it estimates that it got a return between £11.5-13.1bn to the UK economy (Innovate UK, 2016). Applying Porter (1990) 'Diamond od National Advantage' it seems that investing in developing and manufacturing BEV and FCEV is an obvious choice for the UK. There is excellence in powertrain engineering, good infrastructure and an engine manufacturing industry that will need to transition towards alternative powertrains (factor condition) which is aligned with the Government Industrial strategy; there is a high demand for conventional automobiles in the home market (demand conditions) and unless factors of production are converted to these types of vehicles, sales will benefit foreign companies; there is also a strong supply chain for conventional cars and as electric cars are simpler, it will be easy to adapt; and the national environment facilitates the creation of new companies, clear organisational rules and enough domestic rivalry to stimulate competition (firm strategy, structure and rivalry).

As Porter (1980) identified, differentiation offers the possibility to charge a premium which may lead to higher profitability. Also, following the technology cycle model from Tushman (1997), it seems clear that we are now living in a period of technological discontinuity, where electric powertrains might soon become the next dominant design. For this to happen, some degree of collaboration between vehicle manufacturers is necessary as R&D can benefit the whole industry. Also, because fuel cells are critical components to FCEV, automotive companies seek to reach strategic alliances with the companies that work with FCs. The same is true for BEV and battery manufacturers (this was illustrated in *Table 5*. This often results in open innovation where companies open source some intellectual property to contribute to the development of the sector as a whole. For example, Tesla did this with part of its IP in 2014 (Musk, 2014); however, the company still holds much IP in regards to autonomous driving technology.

Companies must be aware of long-term automotive technology roadmaps, where the UK and other countries expect FCEV to dominate as part of the move towards the hydrogen economy by 2050 (Automotive Council UK, 2013; King, 2007a; METI, 2016a). To reach that goal, interim roadmaps can facilitate the integration of the new technology into the business, support company strategy and planning processes, identify gaps in the business and identify new opportunities such as the development of new powertrain technologies. Having said that, it is likely that if disruptive innovation happens in the area of energy storage, either in battery technology or hydrogen, one technology could make the other obsolete.

Bessant and Tidd (2011) indicate in their 4Ps of innovation framework that there are four innovation dimensions (process and product innovation, and innovation through paradigm shifts and repositioning). Following this model, it is clear that all vehicle manufacturers have historically focused mainly on **product and service innovation**. This includes the design of new cars, improvements in energy economy, and in the context of BEV extend vehicle range and reducing recharging times. Tesla offers 400 kWh of free electricity to new buyers of their vehicles, and Honda and Toyota offer free hydrogen when leasing their vehicles in the USA. These are examples of service innovation.

Process innovation relate to changes in the ways in which products and services are created. A good example of this is Tesla Gigafactory, a battery manufacturing plant, where batteries are produced and delivered much cheaply than the competition.

Position innovation relates to changes in the context in which the products and services are introduced. Despite that BEV are more expensive than ICE vehicles, all brands are trying to appeal to the mass market, including Tesla now with the upcoming Tesla 3, a model with prices around $35,000, instead of the typical price over £61,000 of the Model S. Automakers may need to consider the trend that indicates that while until recently owning a car was a symbol of status, new generations are less appealed by car ownership and value more the service that a car can provide. In a new future, people might be more interested in mobility-as a service, a new e-mobility opportunity that will force some companies to adopt a different market position.

This could also lead to a **paradigm innovation**, a change in mental models which frame what organisations do. Mobility as a service (MaaS) is a type of servidisation that could change how automakers operate and illustrates this paradigm innovation idea.

3.2.1. Managing innovation

Bessant and Tidd (2011) state that the creation of innovation routines contribute to their success. They suggest that firms must be able to recognise when and how to destroy them and start new ones. This is aligned with the idea of 'creative destruction' presented by Schumpeter (1950). Bessant and Tidd (2011) describe a model to convert ideas into successful innovation. They suggest that this can be achieved following four simple phases: searching ideas, selecting the best ones, implementing them and capturing their value.

Searching consists in exploring internal and external threats and opportunities for change. This can be new technological opportunities, such as electric powertrain vehicles, policy changes (e.g. lower carbon emissions levels for cars), or competition changes (competitors selling these vehicles). Innovation strategies could be the outcome of a technology-push or market-pull. Examples of technology driven innovation include technology breakthroughs (often as a result of R&D investment), that in the case of the automotive industry could be the launch of a new car feature (e.g. regenerative braking). Market driven innovation is when companies develop a product because the market is demanding a new product or service (e.g. higher capacity batteries in BEV cars or new infotainment systems). At this step it makes sense to use strategic tools to understand the internal and external environment as well as conducting market research and audits of capabilities.

Selecting consists of choosing which opportunities and threats to respond to. These must be aligned with the overall business strategy and consistent with the organisation's capabilities. The decision might require new knowledge that may need to be developed, otherwise the innovation may fail. For example, companies operating in the luxury car market, might foresee opportunities entering the electric car market; however, if in the near future, this is commoditised due to the arrival of autonomous cars, then this move might not support the generic strategy of the business. Therefore, alignment between business strategy and innovation strategy is fundamental. In this stage it reasonable to use decision making techniques.

Implementing is about doing something new (internally or externally) which requires to acquire new knowledge and launch the innovation. This entails coordinating all the new knowledge areas and execute the project. By doing this, uncertainty decreases and knowledge gaps are filled with new knowledge. To promote, develop and sustain innovation, it is necessary to embed the right values and behaviours within the organisation. Often, there might be resistance to change and therefore managing change may be critical to guarantee the success in the implementation of the innovation process (these challenges are discussed in Section 3.3). Also, it is important to nurture those who can contribute to the creative process and challenge conventional views. In this step, it is good practice to use project management processes. Bessant and Tidd (2011) suggest that co-creating (co-evolution) with customers, increases innovation quality and adoption rates.

Capturing value from innovation is based on building a knowledge base and improving the innovation management process. Value could consist on improving profitability, increasing market share, reducing costs or making a better world (e.g. social innovation). IP can improve the chances of capturing value, as well as, tacit knowledge (tacit seems to be the only way for companies that benefit from open innovation). Even when innovation fails, the lessons learnt (of success or failure, technological or regarding processes and capabilities) can be valuable to sprout the next round of innovation.

3.3. Managing Change

Lewin (1947) change management model is based on three stages[21]. The **unfreeze** stage consists in providing the rationale for change and creating some emotional response from staff by challenging everything about the company (processes, values and culture) and the workforce. The company has to ensure that employees are ready for change and it has to reassure them about the safety of the changes. At this stage, 'force field analysis' can provide an overview of the forces for and against change. Also, a useful model here is Porter's Five Forces model. In the **moving**

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[21] The model uses a metaphor. To arrive to an ice cube with conic shape, parting from cubic ice cube, it is necessary to first unfreeze, then change the shape of the water container to a cone and then freeze again.

stage the company executes the changes and employees begin to accept and adopt change. The **freeze** stage is when change stabilizes and it is safe from regression. Employees are used to the new processes and the company must ensure that the changes become permanent. At this stage new evaluation and new recruitment and promotion systems are implemented. This perspective of change management too simplistic and traditional in the sense that it is linear and does not account for the complexities of the current business environment.

Beckhard (1969) discussed change in the culture of organisations and the strategies for managing it. He promoted the development of the 'Change Formula'[22], a formula that postulates that for change to succeed, the cost of the resistance to change must be weaker than the dissatisfaction with the status quo, the vision for the future of the firm and taking immediate steps to achieve the desired state. He recommended empowering people as agents of change as they tend to support what they create.

Porter (1990) indicated that 'leaders believe in change, they energise their organisations to innovate continuously; they recognise the importance of their home country as integral to their competitive success and work to upgrade it' and concluded that nations and companies should continuously aim at achieving international competitiveness.

Kotter (1996) developed a sensible change management model known as the 'Eight Step Model'. The first step consists in **establishing a sense of urgency** for the need for change. This is likely to steer some motivation. For example, companies that have not yet entered the electric vehicle market should discuss recent developments in this area and what the competition is doing. A SWOT analysis identifying the main threats and opportunities might be beneficial. Also, creating roadmaps can help to create this sense of urgency. Furthermore a PESTLE can also identify environmental factors that may strengthen the need for change. The second step consists in **creating the guiding coalition** with influential colleagues that can contribute to leading change. Forming a team with the key people can help to create momentum. It is important that they are committed and good team players. At this stage, it might be useful to evaluate the Belbin (1999) roles of the members to ascertain that the mix of people is likely to be most efficient. A large enough group

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[22] The formula was originally created by David Gleicher.

from different areas of the organisation can also help to spread the sense of urgency. The third step involves **developing a vision for change** simple enough for everybody to understand it and interiorise it, and the strategy to achieve that vision. The fourth step is about **communicating the change vision**. The vision needs to be promoted as much as possible and it helps to link operations to the vision, as this increases its visibility. Also, the team members must become role models. The fifth step entails **empowering others to act on the vision**. This might require removing obstacles, including systems or structures detrimental to the vision of change. Kotter (1996) identified the role of what he called ‘sleepers, blockers, preachers and champions’, in bringing change. Influence (or eliminate) staff blocking the changes can help to eliminate barriers to change. At this stage, risk seeking and unconventional thinking is encouraged. The sixth step consists on **generating short-term wins**. Quick successes can help to motivate staff and reduce the arguments for those who oppose change. This means that some short-term targets have to be defined in a SMART ways (specific, measurable, achievable, realistic and time bound). For example, if the long-term goal is to commercialise a BEV with a range of 1,000 km, the short-term goal can be increasing range by 100 km within six months. At this stage, it is important to reward those who contribute to achieve the wins. The seventh step comprises the **consolidation gains and producing further change**. After some quick wins, the change vision gains credibility and it facilitates changes in all systems, structures and policies that are not aligned with the vision. At this stage hiring new talent can help to speed up the change while enabling new projects. The outcome of this stage is achieving long-term goals, not simply the short-term wins. During this time, implementing a continuous improvement philosophy (Kaizen) in the organisation can support further changes. The eighth step consists in **anchoring new approaches in the culture** by creating better performance, leadership and effective management. Change must become an integral part of the organisation culture. The connection between organisational change and success must be communicated to current and future employees and promote change values on the workforce. For example, Toyota pioneered Kaizen practices, a core principle that is now embedded in the organisation culture and that defines the company slogan ‘Always a Better Way’ (Toyota, 2013).

Higgs and Rowland (2005) found that most change initiatives fail mostly due to lack of commitment from staff, poor processes or wrong assumptions. Higgs and Rowland (2005) and Higgs and Rowland (2011) state that linear approaches to change and leader centric behaviours tend to fail (in contrast to emergent approaches). They created a change leadership framework and some guidelines regarding how to make choices on change approach (directive, master, self-assembly and emergent) based on the magnitude of the changes needed. They found a systematic failure of self-assembly and the success of emergent change approaches.

Dodgson, Gann, and Salter (2008) estates that innovation strategy guides decisions about how an organisation resources and competences are used to meet the objectives for innovation while building a competitive advantage. Innovation strategy is about monitoring the business environment, understanding major technological trajectories, developing and organising competences and evaluating and investing in those. This principles have some commonalities with other theories and can benefit from the use of similar tools to the ones highlighted in the strategy section (e.g. roadmaps, PESTLE, Porter 5 forces, etc.).

The classical approaches to change management are linear. In them, the leader is an agent of change. This is a top-bottom approach where the manager directs and intervenes with the aim of creating economic value. In contrast, emergent approaches to change management recognise the complexity of the business environment and seek more involvement from the work force. The goal is creating value and capabilities. The leader dialogues (is a sense maker) and is a mentors that facilitates change anywhere in the organisation. This approach seems to be more successful in complex and differentiated changes, such as the ones required in disruptive innovation.

The CIPD identifies that techniques to design change, build understanding and managing change are essential aspects of transformational change. Change management is ‘a process that requires relational leadership, building trust, voice and dialogue, and maintaining emotion, energy and momentum’ (Balogun, Hailey, & Cleaver, 2015). It involves creating change advocates, removing obstacles and providing tools, and acting on measurements. These principles seem inspired in the ones advocated by Kotter (1996).

4. Methodology

The methodology included four main stages. During the first stage a comprehensive market research was conducted to obtain the technical, economic and environmental parameters necessary to populate the models. This involved gathering information from secondary sources, typically available on vehicle manufacturers' websites and other commercial literature, statistical data from governmental sources and other independent third parties.

The second stage deepen the understanding of the sector and it consisted on attending to an event where questions were asked to the participants in a conference. This produced a better understanding of the current state of the UK electric car market. A summary of the main findings of the event appear in Appendix X. Further background information was obtained by attending to working meetings with Hydrogen London, a centre for expertise for hydrogen and fuel cell technology promoted by London Greater Authority.

The third stage included semi-structured qualitative face-to-face interviews with two automakers and two commercial fleet customers, used as case studies. The interviews were conducted over one day in the context of an industrial event. This reduced the costs of the process, ensured the engagement of the respondents and became a convenient approach as the respondents had to attend to the event anyway.

The goal of quantitative corporate interviews is to understand the behaviour of the firm in the context of its competitive strategy, relationship to its markets, product technology, production methods, and the behaviour of the competition (Schoenberger, 1991). This method can provide insights for the generation of hypothesis testing to explain business behaviour and despite that statistical generalizations cannot be made, the method enables analytical generalisations relevant to the theoretical propositions.

The interviews consisted of questions focus on particular areas that needed to be explored but they gave the interviewees plenty of scope to elaborate their responses according to their level of expertise. The interviews were conducted face to face, as this offers a higher response and lower abandonment rates than on-line and telephone interviews (Bryman, 2015; Holbrook, Green, & Krosnick, 2003). According to Bryman (2015), face to face interviews are suitable for long and complex questionnaires, and they enable the interviewer to interpret visual cues (body language and reactions). Besides, questions can be tailored in-situ, leading to meaningful discussions and enabling respondents to be probed. Face-to-face interviews decrease non-response bias, and are typically more expensive than other types of interviews (e.g. telephone interviews). A list of the questions asked to the participants appears in Appendix XI.

On the negative side, semi-structured face-to-face interviews are likely to take longer as there is more room for interpreting questions in a broader way. This can result on deeper insights beyond of the aim of the original questions. Furthermore, the interviewer biases may pass unnoticed and there is a higher risk of stage fright on both sides. According to Holbrook et al. (2003) face-to-face respondents are less suspicious than telephone ones, more cooperative and engaged in the interview process.

The reason for the selection of the two automakers was double. Firstly they both commercialise BEV and FCEV and this offers more guarantees of unbiased responses than manufacturers producing just one type of technology. Secondly, because there are just three global manufacturers of FCEV worldwide and the two respondents are the only ones selling these cars in the UK market. The two fleet operators were chosen because they were two of the largest consumers in the UK of FCEV for these two automakers and they also operate BEV. Therefore they have expertise operating both technologies and they could compare and contrast fairly.

The fourth stage consisted on a follow-up questionnaire for clarifying and validating the quantitative assumptions taken in the costing models.

Based on the case study of these four organisations, the outcome of the interviews and follow-up questionnaires identified two main types of customers (private and commercial fleets) and four main financing methods (straight purchase, hire purchase, contract hire, contract purchase and buy back).

The case study method has been an essential research method in management and it has been used among other areas in business research and technological development (Chetty, 1996). A case study is a systematic research tool that represents a research strategy (R. K. Yin, 1981) and in this case combines qualitative and quantitative evidence. The possibility of collecting data from different sources (e.g. commercial information, interviews, direct observations) is one of the main strengths of this method (Chetty, 1996). Case studies should be regarded as experiments as they do not represent a sample. One of the aims of the investigator following this methodology should be expanding and generalising theories (analytic generalisations) and not to conduct descriptive statistics (e.g. analysing frequencies; statistic generalisations) (R. Yin, 1984). As a research strategy, it examines a contemporary phenomenon in its real-life context, overall when the boundaries between phenomenon and context are not too evident. R. K. Yin (1981) classifies case studies as exploratory, descriptive and explanatory. These case included in this study constitute descriptive research that explains and explores further insights about the differences between BEV and FCEV from an economic and operational perspective. R. K. Yin (1981) argues that a case study includes answers to a number of open-ended questions that enables the reader to find the necessary information easily.

For Chetty (1996) case study methodology permit the study of decision making processes and causality and it is indicated when asking ‘how’ and ‘why’ questions. For example, how is the marketing mix of an automaker tailored to highlight the unique selling point of BEV or FCEV. She also concludes that the case study method allows the firm to be assessed from multiple angles rather than single variables and as several data collection methods can be combined this gives a better prospect to examine the firm in higher depth than other narrow quantitative methods.

5. Results

This Chapter presents the results of a techno-economic and environmental comparative analysis between BEV and FCEV, as well as, the impact that two of the key raw material components (lithium for BEV and platinum for FCEV) can have on vehicle production levels. The results are based on three case studies. The first one relates to private buyers. The other two are inspired on the responses from two automakers and two of their fleet customers. One of the cases considers a fleet operator that acquires vehicles via contract purchase. The other is based on a similar but smaller company that funds the sourcing of its vehicles via contract hiring (leasing).

The methodology for the financial assessment is explained in Appendix XII, which describes how to calculate the net present total cost of ownership and the different types of contract available for the procurement of vehicles by private and corporate buyers. Appendix XIII explains the methodology to calculate the total cost of ownership of the vehicles, according to the financial product used to procure them, the payment schedule for each type of charge during the life of the vehicle and the main assumptions used in the costing models.

Vehicles’ embedded GHG emissions have been calculated following the lifecycle assessment methodology. This includes the embedded footprints from manufacturing and disposing the vehicles, as well as, the ones from operating them (on a well-to-wheel basis). Details explaining the methodology followed and assumptions made appear in Appendix XIV.

5.1. Private Cars (Case study 1)

5.1.1. Techno-Economic comparison between BEV and FCEV for private consumers

The economic performance indicators of BEV and FCEV bought by private consumers are illustrated in Table *9* and Table *10*, respectively. The figures to calculate the net present total cost of ownership (NPTCO) are the ones found in Appendix XV (Table *38* and Table *39*)**.**

BEV are much more efficient than FCEVs. The energy consumption of the BEV is around 24-40 kWh/100 miles (Table *4*), which is half of the one of FCEV (59-81 kWh/100 mi), as shown in Table *6*. The average annual energy consumption (in

2017) for the sample of BEV is around £411/year and the fuel costs for the average FCEV is considerably higher (£1,181/year). In contrast, annual fuel costs for a Volkswagen Golf 1.8L (gasoline)[23] are around £1,744/year.

Table 9. Economic key performance indicators of BEV for private buyers.

Brand	Model	NPC (£)	NPC(£) /100 mi	£/mi of Range	£/Power Load[24]
BMW	i3 BEV/60 (A)	38,472	24.54	475	4,024
BMW	i3 BEV/94 (A)	40,166	25.62	352	3,738
Chevrolet / Opel	Bolt /Ampera-e	39,742	25.35	167	3,669
Fiat	500e	33,068	21.09	394	2,094
Ford	Focus Electric Hatch	39,832	25.40	346	2,580
Hyundai	IONIQ Electric	36,927	23.55	298	2,288
Kia	Soul EV	38,774	24.73	417	2,007
Mercedes	B250e	45,250	28.86	520	3,463
Mitsubishi	i-MIEV ES	25,570	16.31	433	1,071
Nissan	LEAF S Acenta	39,774	25.37	372	2,121
Smart	ForTwo Electric Drive	29,231	18.64	432	1,649
Volkswagen	e-Golf SE	34,860	22.23	293	2,199
Tesla	Model S 75	83,723	53.39	336	7,665
Tesla	Model X AWD 75D	98,113	62.57	412	7,920

Table 10. Economic key performance indicators of FCEV.

Brand	Model	NPC (£)	NPC(£) /100 mi	£/mi of Range	£/Power Load[24]
Honda	Clarity Fuel Cell	83,421	53.20	228	5,738
Hyundai	Tucson FC / ix35	74,368	47.43	281	3,305
Toyota	Mirai	81,417	51.92	261	4,973

The cheapest BEV is the Mistubishi i-MIEV (16 pence/100mi) and the Smart Fortwo (19 p/100 mi); however, these are mini and subcompact cars respectively. The most expensive ones are the Tesla models (53-63 p/100mi). The differences in price between FCEV are less extreme than among BEV. In both cases, the residual values have been considered as zero but this could not be the case. So far, there is no evidence of the resale value of any of both technologies after 14 years.

To compare the costs between BEV and FCEV of different class fairly, the Toyota Mirai is compared with the BMW i3/94(A), as both have similar power, class and number of seats (4). The BMW i3/94(A) is less than half the price of the Mirai. The

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[23] Assuming 12.87L/100 mi, price of petrol £1.21/L.

[24] Power loading is the weight-to-power ratio (vehicle weight in kg / max power in kW)

remaining models are more difficult to compare because of the differences in power, vehicle class and number of seats. The average NTCO of BEV and FCEV with 4 seats is £34,319 and £82,419 respectively. Similarly, the NPTCO of 5 seat BEV (excluding the Tesla model S75) is £39,309 and the cost of the only 5 seat FCEV is £74,368. FCEV bought in 2017 are likely to cost more than double than BEV models. For example the BEV with 4 seats are 58% cheaper and 47% for cars with 5 seats (excluding the Tesla models).

Another interesting metric to consider is the cost of a vehicle considering its maximum range. The cheapest car per mileage of range is the Opel Ampera-e (£167/mile of range), even more so than the FCEV models (£228-£281/mile of range). This is possible because the Ampera-e offers the longest range among BEV at the average cost which is more than half of a FCEV. The EPA driving cycle was used, instead of the NEDC, as the latter is very un-realistic. Range differs very much depending on the type of driving cycle, as well as, ambient temperature (e.g. if the air conditioning or the heating is on, range is reduced dramatically), in addition to vehicle mass, drag coefficient, rolling resistance, frontal area of the vehicle, acceleration and gradient of the roads (Velazquez Abad, Cherrett, & Waterson, 2016). Excluding the Opel Ampera-e FCEV perform better when considering this indicator.

Most BEV have a range under 150 miles (Table *4*), which allows drivers round trips of 75 mi or up to 270 miles if they recharge 80% of the battery at their destination with a supercharger. *Figure 21* shows that in terms of range, FCEV are the clearly superior to BEV. However, Tesla Model S 75 and the Opel Ampera-e offer both 249 and 238 miles of range, and this is just 16 and 27 miles less, respectively, than the Hyundai ix35 (in the case of the Ampera-3, at almost half the price).

Figure 22 illustrates the premium that customers pay for having larger batteries and the time penalty that this involves. Typically, FCEV refuel in around 3-5 minutes. In contrast, an average BEV with an on-board 240VAC/3.3kW charger takes 8 hours in recharging (this excludes the Tesla models from the sample), around 4 hours with a 7.6 kW one and under 1 hour with a DC/50 kW superfast charger[25]. Tesla models take considerably longer in recharging, but this is a factor of the power of the

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[25] A Tesla Model S with a 90 kWh takes just 40 minutes to charge 80% of the capacity of the battery

charger, rather than the battery itself. Upgrading to a 11kW or 16.5 kW Tesla Wall Connector would reduce charging time to around 6½ or 5½ hours, correspondingly.

5.1.2. GHG LCA Comparison between private BEV and FCEV

The LCA emissions of the BEV and FCEV assessed in this study are reported in Table *11*. BEV and FCEV produce zero emissions at the point of use (TTW or scope 1 emissions), as explained in Chapter 1. However, manufacturing vehicles and well-to-tank emissions from energy and hydrogen consumption is significant. Embedded GHG emissions show that FCEV have a much higher footprint (12.4-13.7 tCO_2e/vehicle) than BEV (5.7-11.6 tCO_2e/vehicle). This is also the case when normalising by vehicle-weight (Figure *23*). Lifetime WTT emissions of BEV (scope 2) are half (in most cases) of the emissions from FCEV (scope 3). This is for two reasons. Firstly, BEV powertrains are more efficient than FCs, and therefore less energy is needed to do the same work. Secondly, because the carbon intensity of producing (SMR with no CCS), transporting (compressed H2 transported by road) and dispensing hydrogen is much higher than the one of the UK power grid during the lifetime of the vehicles (2017-2030). Nevertheless, the implementation of a green hydrogen standard and the successful deployment of a market for guarantees of origin agreements could potentially decarbonise hydrogen by giving access to more environmentally friendly production pathways. Also, the adaptation of the UK gas network to carry hydrogen could improve the efficiency a further around 2.5 percentage points.

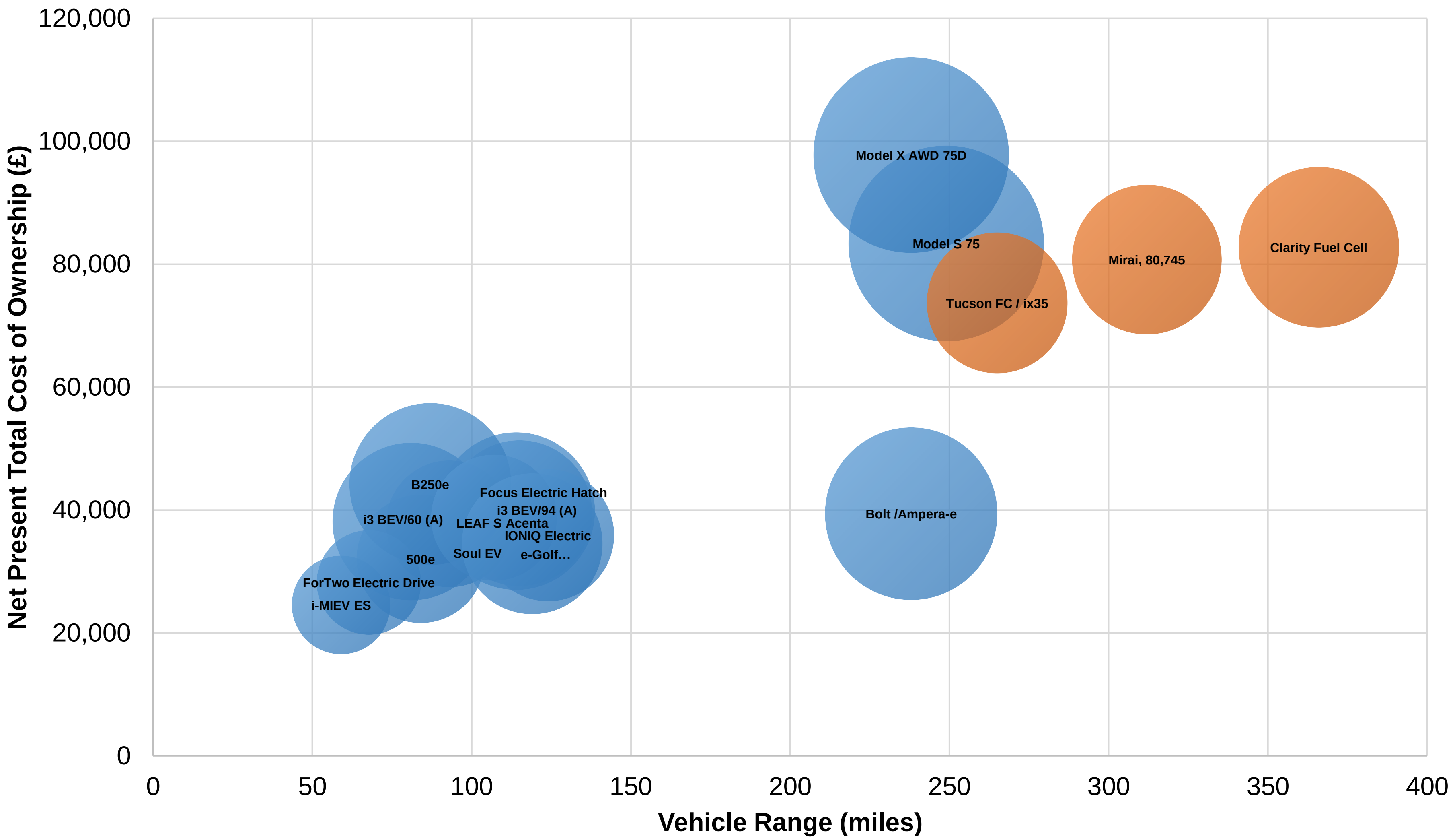

Figure 21. Net present total cost of ownership BEV and FCEV versus range. The diameter of the circles is proportional to the power of the motor. The diameter of the bubble relates to the size of the motor.

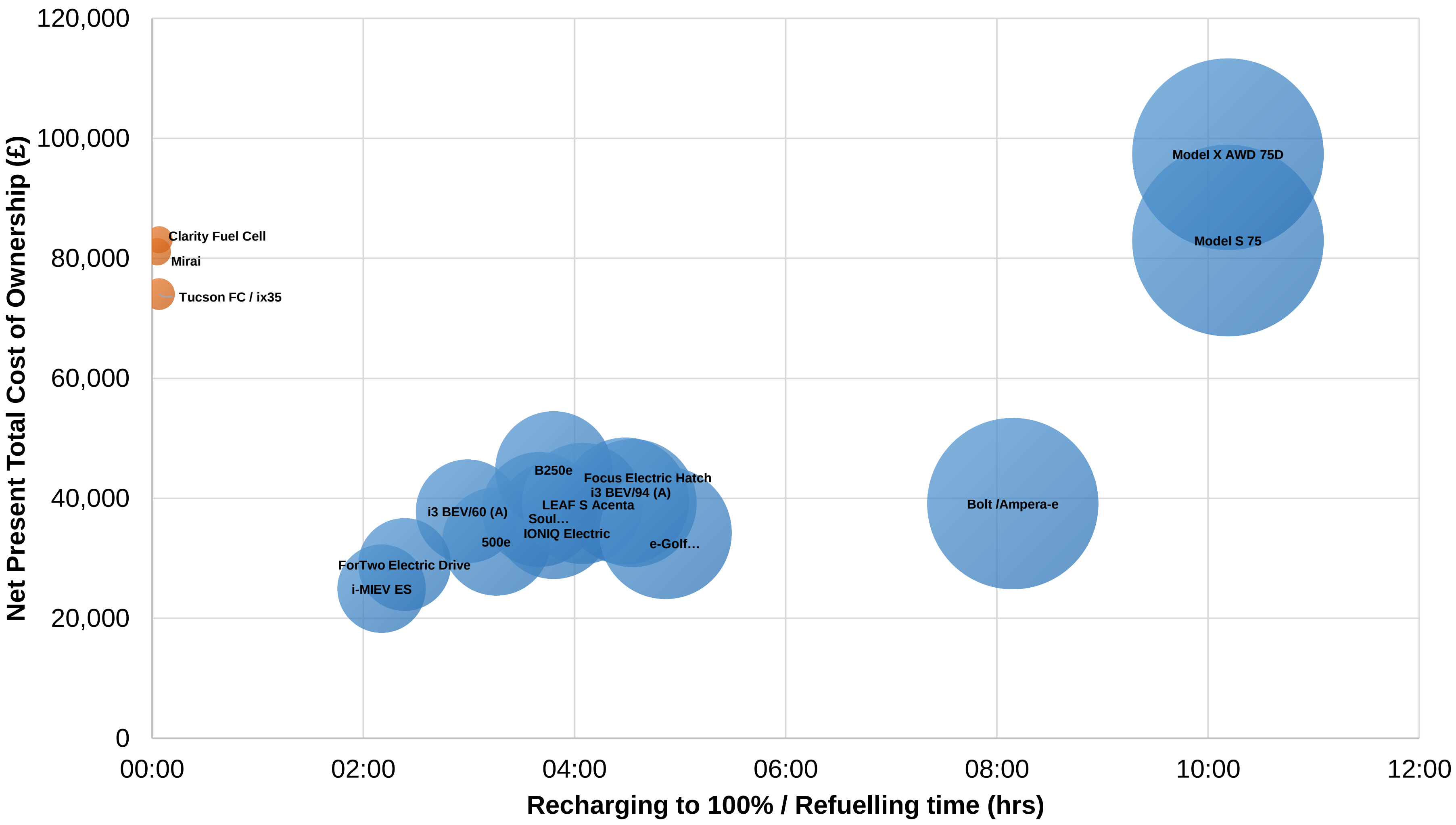

Figure 22. Net present total cost of ownership BEV and FCEV versus recharging time (deomestic charger 7.4kW). The diameter of the circles is proportional to the power of the motor. The diameter of the bubble indicates the size of the battery of the BEV.

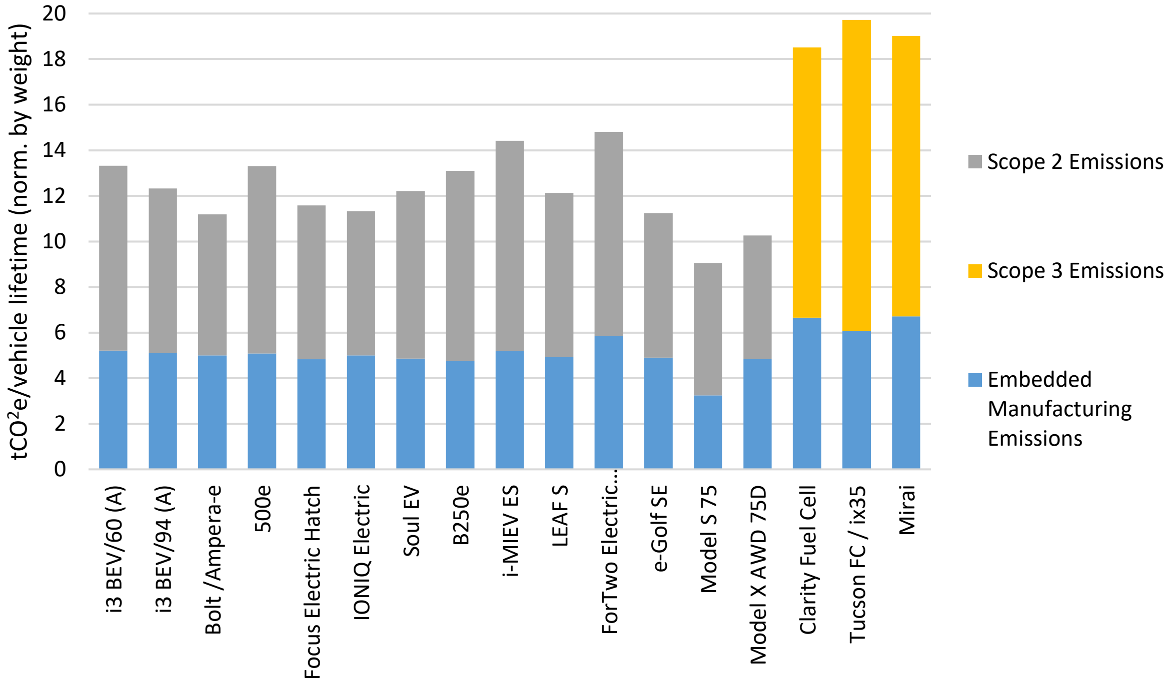

Figure 23.LCA emissions of private BEV and FCEV normalised by vehicle weight.

Table 11. LCA GHG Emissions of BEV and FCEV (tCO_2e/vehicle lifetime).

Brand	Model	Embedded Emissions	TTW GHG Emissions	WTT GHG Emissions		WTW
			Scope 1	Scope 2	Scope 3	All
BMW	i3 BEV/60(A)	6.22	0	9.70		15.92
BMW	i3 BEV/94(A)	6.85	0	9.70		16.55
Chevrolet	Bolt /Ampera-e	8.11	0	10.06		18.18
Fiat	500e	6.66	0	10.78		17.44
Ford	Focus Electric	7.99	0	11.14		19.13
Hyundai	IONIQ Electric	7.09	0	8.99		16.08
Kia	Soul EV	7.61	0	11.50		19.11
Mercedes	B250e	8.20	0	14.38		22.58
Mitsubishi	i-MIEV ES	6.08	0	10.78		16.86
Nissan	LEAF S	7.40	0	10.78		18.18
Smart	ForTwo Electric	5.71	0	8.73		14.44
Volkswagen	e-Golf SE	7.76	0	11.50		17.82
Tesla	Model S 75	6.85	0	12.94		19.07
Tesla	Model X AWD 75D	9.87	0	10.06		24.53
Honda	Clarity FC	12.48	0		22.43	35.00
Hyundai	ix35	13.69	0		30.67	44.35
Toyota	Mirai	12.40	0		22.77	35.17

6.1.1.1. Resources

Assuming that a battery needs 0.9 kg Li_2CO_3/kWh, a 60 kWh battery requires 54 kg of Li_2CO_3. The GREET model assumes that each kg of Li_2CO_3, contains 188 g of metallic lithium. Therefore, such a battery has 10.15 kg of pure lithium (169.2 g

Li/kWh). Currently, worldwide reserves of Lithium (Li) are around 14.5 Mt and considering that there are almost 1bn cars worldwide, as reported in Table *12*, current Li reserves could cover current demand from batteries. However, at the end of the life of the vehicles, unless all the Li is recycled, current reserves would be depleted.

Despite the fact that reserves can increase by making lithium resources more economically profitable (prices increased by 40-60% in 2015; currently £5,193/ton[26]), USGS (2017a) estimates that total resources might be around 86.9 Mt. Currently, Li production capacity is around 49,400 tons (in 2015). Even if all Li would be used to build car batteries, this would just be enough to make under 4.9 million cars; a small percentage of the total conventional cars sold each year worldwide. To overcome this constraint, automakers must promote Li extraction and processing if they want their sales to grow over that threshold. Strategic alliances and joint ventures between BEV manufacturers and battery manufacturers, and between these and mining companies are expected to secure reliable access to the raw material. Alternatively, automakers should focus on finding alternatives (e.g. anodes made of calcium, magnesium, zinc). Despite the fact that reserves can increase by making Li resources more economically profitable (prices increased by 40-60% in 2015; currently £5,193/ton[27]), USGS (2017a) estimates that total resources might be around 86.9 Mt. Currently, lithium production capacity is around 49,400 tons (as per 2015). Even if all Li would be used to build car batteries, this would just be enough to make under 4.9 million cars; a small percentage of the total conventional cars sold each year worldwide.

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[26] 1 GBP = 1.23 USD

[27] 1 GBP = 1.23 USD

Table 12. Quantification of the lithium needed to build Li-ion batteries and its long-term surplus.

Parameter	Quantity	Source
Metallic Lithium (g Li/kWh)	169.2	GREET Model
Size battery (kWh)	60	Example of vehicle with 238 miles range
Total Lithium (kg) / battery	10.15	Own calculation
Total cars in use worldwide (2014)	907,050,941	OICA (2016)
Total Li needed (tons)	9,208,381	Own calculation
Total Reserves (tons in 2016)	14,469,000	USGS (2017a)
Surplus reserves	5,260,619	Own calculation

As explained in Chapter 2, PEMFC use platinum as catalyst to enable and accelerate the reaction between H_2 and O_2 to produce power. Platinum (Pt) is a very expensive metal (£25,615/kg[28]) which is used in very small amounts in PEMFC. As commented in Chapter 2, most Pt is produced in South Africa and labour unrest can disrupt the supply chain. Therefore, there are risks associated with sourcing this material as it is very concentrated in one single country. Besides, there is a strong demand for this metal from conventional automakers, as it is also used in three way catalytic converters for reducing NO_X emissions. USGS (2017b) estimates current annual Pt production worldwide at 172,000 kg. Considering that each PEMFC is loaded with 22.67 g of Pt, annual production allows the manufacturing of 7,587,119 fuel cells, and therefore vehicles (*Table 13*). To put this in perspective, the annual production of cars worldwide is around 72 million cars (OICA, 2017). FCEV makers need to ensure access to this resource and at reasonable prices, and even getting all the Pt produced in the world, they would only cover 10% of the cars made each year. With strategic alliances and partnerships, production levels could be scaled up. However, with current car ownership levels, there is enough Pt to renew the car stock three times. In this research, the average life of FCEV is 14 years, which means that in 45 years the reserves would be depleted (unless Pt is recycled, and assuming that there is no competition from other industries).

Comparing both technologies, it seems that FCEV are better positioned than BEV to reach higher annual production levels (7.5 M vs. 4.9 M cars). In the long term, according to current reserves and excluding recycling, there is enough Lithium to

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[28] 1 GBP = 1.23 USD

supply the total number of cars in use worldwide for 22 year (if all those cars were BEV) vs. 45 for FCEV. This assumes that 100% of the resources are used to produce BEV, which in itself is not realistic, which suggests that depletion could occur much sooner (unless all materials are recycled). All these factors highlight that BEV and FCEV production can only be residual nowadays even if prices were low. Partnerships and alliances are necessary to get those materials. An alternative solution to the potential scarcity of raw materials is reducing the load of these in current battery and fuel cells and developing new technologies capable of operating with different ingredients.

Table 13. Platinum needed to build PEMFC and its long-term scarcity.

Parameter	Quantity	Source
Total Platinum (g/ FC unit)	22.67	GREET Model
Total cars in use worldwide (2014)	907,050,941	OICA (2016)
Total Pt needed (tons)	20,572	Own calculation
Total Reserves (tons in 2016)	67,000	USGS (2017b) (all PGM)
Surplus reserves	46,428	Own calculation
Total Li (5kWh battery) (tons)	767,365	Own calculation

5.2. Commercial Fleets (Case study 2 and 3)

Commercial fleets have very different operations depending on whether they are in the business of renting cars, they used them for private hiring (e.g. taxi/chauffeur services) or for the use of their own employees. Furthermore, the way of financing those vehicles may result in different NPTCO (e.g. contract purchase, leasing or buy back schemes) that may end in a powertrain technology becoming cheaper than the other. The evaluation of the responses for this research has led to the creation of the next two case studies. In both cases, the vehicles are operated by these companies for 3 or 4 years and after that, depending on the type of contract, they sell the cars or return them to the lessor.

5.2.1. Techno-Economic comparison between BEV and FCEV for fleet operators

CASE 2

Case 2 represents a company that hires vehicles privately (taxi/chauffeur services) and funds the procurement of the vehicles via a contract purchase. How a contract purchase works is explained in Table *27*. The main assumptions for this case study appear in Appendix XVI (Table *40*). In the example, it has been assumed that corporate buyers can get a 10% discount on all retail prices (purchasing, chargers, maintenance) due to their large purchasing volume which gives them a high negotiating bargaining power.

Table *41* and Table *42* show the periods in which the payments for each concept are made (BEV and FCEV, respectively). The costs of each element included in the NPTCO appear in Table *43*. Based on the results of the market research and the primary data provided by the respondents, the NPTCO of BEV and FCEV are illustrated in *Table 14* and

Period		**0**	**1**	**2**	**3**
Year			**2017**	**2018**	**2019**
Mileage		0	32,000	64,000	96,000
Capex	**Deposit (30%)**	7,339			
	Monthly Payments		3,728	3,728	3,728
	Option to Purchase fee	10			
	UK Subsidies	-4,500			
	Fast Charger + Installation	0			
	Option Final Payment				7,339
	Resale value				-3,293
Opex	**VED**		0	0	0
	Electricity				
	Service Contract		151	151	151
	Tyres		257	257	257
	Battery replacement				
	MOT				55

Table 15, respectively. The costs of electricity are around £1,096-£1,805/year[29] and cost of hydrogen refuelling £3,000-£4,094/year but based on this case study, energy costs are paid by the drivers, as well as insurance premiums, and therefore all these expenses are excluded from the calculations, and to large extent irrelevant for the fleet owner.

In contrast to Case 1 (private customers), case 2 shows that as the vehicles have not reach the end of their lives, residual values make a significant difference between BEV and FCEV. Excluding the Tesla models, and the mini cars, the average NPTCO of all BEV and FCEV is £19,735 and £29,675, respectively. The price differential is just £3,313 per year which strengthens the business case for FCEV as they can be more available than BEV (due to shorter recharging times).

Table 14. Economic key performance indicators of BEV for commercial fleet owners.

Brand	**Model**	**(Excluding 1st Year Allowances)**		
		NPTCO (£)	**NPTCO (£) /100 mi**	**£/mi of Range**
BMW	i3 BEV/60 (A)	19,924	20.75	246
BMW	i3 BEV/94 (A)	20,584	21.44	181
Chevrolet	Bolt /Ampera-e	19,942	20.77	84
Fiat	500e	15,922	16.59	190
Ford	Focus Electric	19,891	20.72	173
Hyundai	IONIQ Electric	18,717	19.50	151
Kia	Soul EV	19,459	20.27	209
Mercedes	B250e	22,739	23.69	261
Mitsubishi	i-MIEV ES	10,967	11.42	186
Nissan	LEAF S Acenta	19,594	20.41	183
Smart	ForTwo Electric	14,163	14.75	209
Volkswagen	e-Golf SE	16,765	17.46	141
Tesla	Model S 75	46,399	48.33	186
Tesla	Model X AWD 75D	56,813	59.18	239

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[29] Range of all models for energy prices in 2017.

Table 15. Economic key performance indicators of FCEV for commercial fleet owners.

Brand	Model	(Excluding 1st Year Allowances)		
		NPTCO (£)	NPTCO (£) /100 mi	£/mi of Range
Honda	Clarity Fuel Cell	31,699	33.02	87
Hyundai	ix35 Fuel Cell	26,556	27.66	100
Toyota	Mirai	30,770	32.05	99

CASE 3

Case 3 represents a company that hires vehicles privately (taxi/chauffeur services) and funds these vehicles via an operating leasing (hire contract). The main assumptions for this case study appear in Appendix XVIII (*Table 48*). The company leases the vehicles for four years and does an average of 35,000 miles/year. The NPTCO of each BEV and FCEV model is illustrated in Table *16* and Table *17*, respectively. Similar arguments to a contract purchase apply. The costs of leasing BEV are lower than FCEV, due to their lower retail price. Excluding the Tesla models and the mini cars, the average monthly rental of FCEV is £858/month, while BEV is £413. FCEV are £445 more expensive than BEV (more than double). Excluding the Tesla and mini cars, the NPTCO of BEV is £21,237, while the cost of FCEV is 32,994. This is a difference of £8,248/year over the four years of the contract hire.

Table 16. Economic key performance indicators of BEV for commercial fleet owners.

Brand	Model	(Excluding 1st Year Allowances)			Monthly Rental
		NPTCO (£)	NPTCO (£) /100 mi	£/mi of Range	
BMW	i3 BEV/60 (A)	21,053	21.93	260	423
BMW	i3 BEV/94 (A)	22,454	23.39	197	437
Chevrolet	Bolt /Ampera-e	22,401	23.33	94	423
Fiat	500e	16,714	17.41	199	327
Ford	Focus Electric	21,831	22.74	190	422
Hyundai	IONIQ Electric	19,754	20.58	159	382
Kia	Soul EV	20,387	21.24	219	399
Mercedes	B250e	23,530	24.51	270	474
Mitsubishi	i-MIEV ES	11,552	12.03	196	210
Nissan	LEAF S Acenta	20,699	21.56	193	404
Smart	ForTwo Electric	14,594	15.20	215	288
Volkswagen	e-Golf SE	19,025	19.82	160	352
Tesla	Model S 75	50,313	52.41	202	924
Tesla	Model X AWD 75D	60,327	62.84	253	1,147

Table 17. Economic key performance indicators of FCEV for commercial fleet owners.

Brand	**Model**	**Without Claiming Tax**			**Monthly Rental**
		NPTCO (£)	**NPTCO (£) /100 mi**	**£/mi of Range**	
Honda	Clarity Fuel Cell	57,711	60.12	158	918
Hyundai	ix35 Fuel Cell	48,867	50.90	184	765
Toyota	Mirai	56,116	58.45	180	890

5.1.1. GHG LCA Comparison between corporative BEV and FCEV

CASE 2

The vehicles from the sample are expected to do 96,000 mi over 3 years. GHG emissions under case 2 are higher than the ones of case 1 (private vehicles) despite that these run for 156,000 miles over 14 years. The reason is that concentrating most of the mileage in the near future yield higher emissions as the carbon intensity of the grid is much higher now that it will be in the medium and long-term future. It has been assumed that the embedded GHG emissions of the vehicles over the 3 years of the contract are proportional to their life expectancy and have been allocated to the business according to the mileage done over the this period.

The embedded GHG emissions for each vehicle of the fleet is 61% of the total, as the remaining footprint is allocated to the new buyer, once the vehicle is resold at the end of the contract (Figure 24). To make a fairer comparison between vehicles, the emissions have also been normalised by dividing the emissions by the kerb weight of the vehicles. This indicates that on a weight basis, over the 3 years, the carbon footprint of FCEV are not considerably higher than BEV.

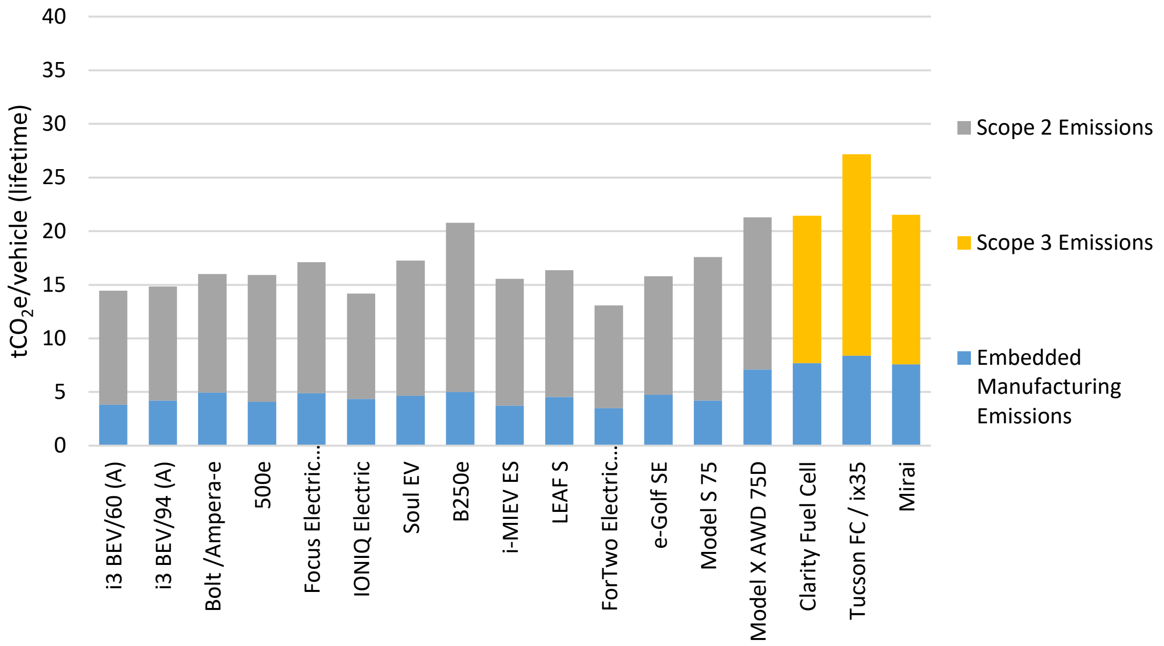


Figure 24. LCA emissions of corporative BEV and FCEV over its 3 years of life.

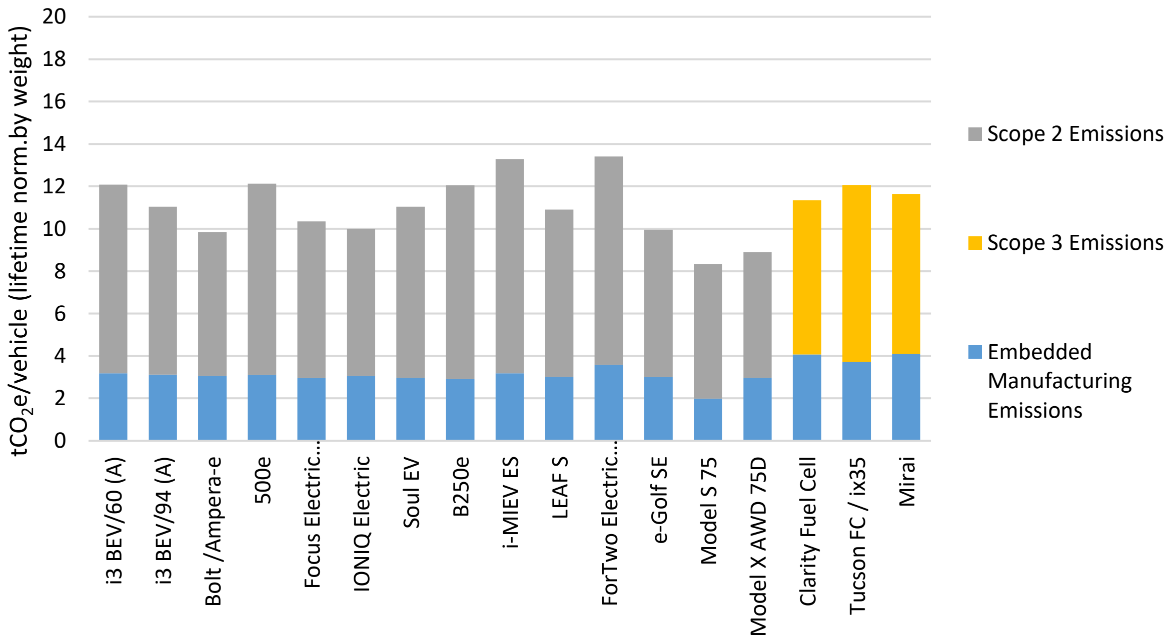


Figure 25. LCA emissions of corporative BEV and FCEV normalised by vehicle weight.

CASE 3

In this case, the total mileage of the vehicle during the lease is 140,000 miles. This represents 89% of the mileage expected during the life of the vehicle, and embedded emissions have been allocated accordingly. GHG emissions from FCEV tend to be larger than BEV (Figure 26), partly because fuel cell cars tend to be heavier than BEV ones. Normalising emissions by weight, FCEV carbon footprint is similar to

BEV. This is because the carbon intensity of the UK power grid in the next four years will still be higher than the one from hydrogen produced via SMR.

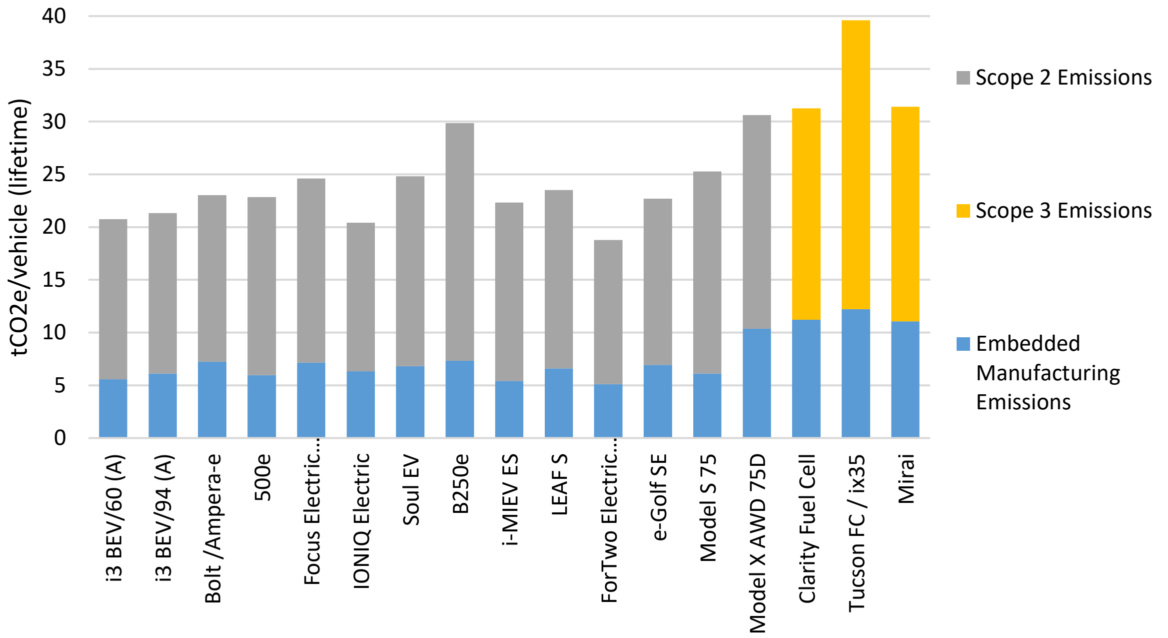


Figure 26. LCA emissions of corporative BEV and FCEV over its 4 years of life.

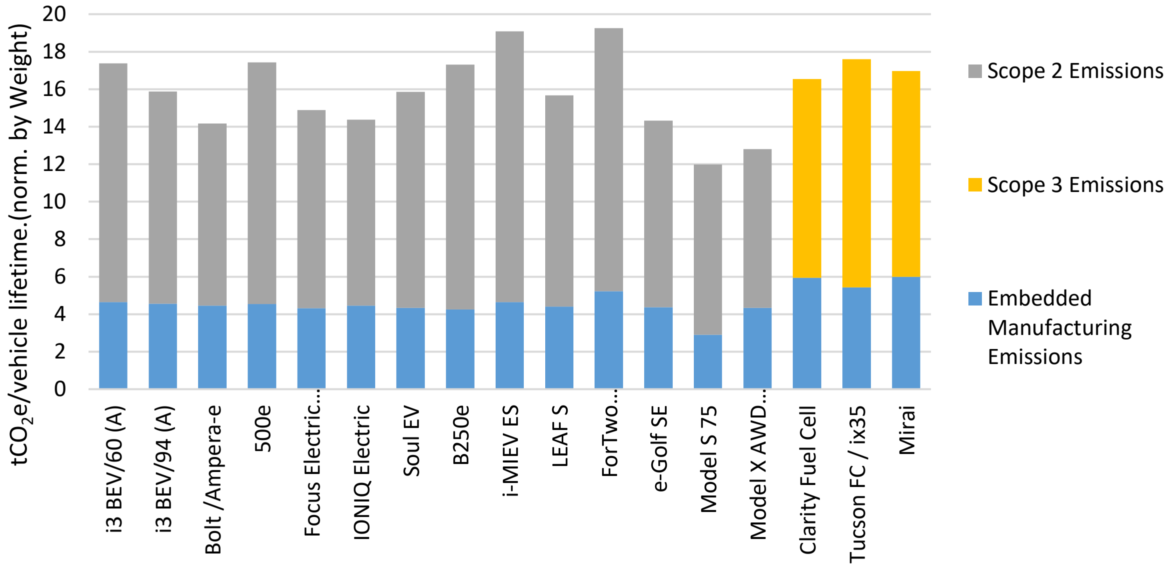


Figure 27. LCA emissions of corporative BEV and FCEV normalised by vehicle weight.

6. Discussion

BEV and FCEV have existed since the middle of the 19th century. Due to challenges that hydrogen faces in regards to energy storage, transportation, lack of refuelling infrastructure and low volumetric energy density, petrol and diesel cars have dominated until now. It is just in the past 5 years that these barriers have started to be overcome, thanks to innovative processes to reduce production costs, and incremental innovations in processes and materials (e.g. catalyst). For BEV the main challenge has been the low gravimetric and volumetric energy density and the high costs of batteries. Developments in battery chemistry have improved this while reducing the costs faster than the markets anticipated. The role of batteries in the selection between BEV and FCEV is bigger than anticipated. The results of case 2 and case 3 suggest that due to the high costs of battery packs, BEV can reach high depreciation at the end of the battery guarantee. If this is changed by a new one, the car could appreciate again, increasing the NPTCO differential in favour of BEV even further. Case 2 suggested that FCEV were 33% more expensive than BEV, but due to operational advantages of FCEV, customers could consider investing in these vehicles. However, under case 3, as the batteries had to be replaced, BEV the differential in depretiation between both types of technologies shortened and FCEV became 60% more expensive than BEV.

The degree to which BEV and FCEV will succeed is still unknown. In countries such as the Netherlands and Norway, grid connected vehicles already represent 9.7% and 22.7% of overall vehicle sales (Goldman Sachs, 2016). Furthermore, as illustrated in *Figure 28*, with globalisation, the rate of adoption of technologies has grown faster each decade. For example, it took just 8 years for HDTV or smartphones to reach an adoption rate from 10% to 90%, therefore, despite the challenges, it seems feasible to reach 100% penetration of BEV or FCEV by 2050. The Coalition (2010) assumed a penetration of 25% FCEV in 2050. The CCC (2016a) expects that by 2027 there will be a stock of 6,645,000 electric vehicles in the UK. In contrast, National Grid (2016) optimistic scenario (Gone Green) forecast 5.8M electric vehicles by 2030 and 9.7M by 2040. As introduced in the results chapter, unless new materials or reserves are found, this forecast seems very optimistic with current lithium and platinum yearly production levels.

One of the key unique selling points of FCEV is the comparatively large range, compared to BEV. However, these differences are shortening as illustrated in Figure *21*, and unless hydrogen tanks increase their energy density, BEV are very likely to catch up by 2020. This has significant importance in terms of strategy. The new Ampera-e has a similar range to the Hyundai ix35, at less than half the price. Therefore, the selling proposition for Hyundai must be around the minimal refuelling time required to fill the hydrogen tank, which allows this vehicle to extend the range immediately. While Tesla differentiation focus strategy focusing on the luxury market by providing a very powerful motor and long range seems to have been successful, new BEV models such as the Ampera-e have eroded the range advantage at half the price. Therefore, Tesla has to produce new models that can compete and for this reason, the Model 3 has been developed. This vehicle will still provide differentiation (e.g. access to proprietary superfast recharging infrastructure) but targets a much broader market segment. Honda and Tesla, both offer free refuelling and recharging (400 kWh) for their customers, which is another example of service differentiation. Innovation must continue to maintain the competitive advantages. Product development resulting in a BEV rechargeable within 5 minutes (without reducing battery life), and providing an autonomy of 400 miles or more is likely provide a considerable competitive advantage and it will disrupt the market in such a way that it will cannibalise sales from ICE and FCEV. This is well represented by the Kano model (Kano, Seraku, Takahashi, & Tsuji, 1984) illustrated in Appendix XIX.

Fuel economy of ICEV is very important for private users. Commercial fleets' operators are less sensitive towards this as it is their customers who pay for the fuel. The annual cost of electricity for an average BEV is comparatively low compared to petrol and diesel of ICEV, and due to the fuel price inelasticity of demand, energy efficiency of powertrains seems a factor less important in the procurement decision making process. For this reason, automakers may consider that other areas present better opportunities to provide a competitive advantage.

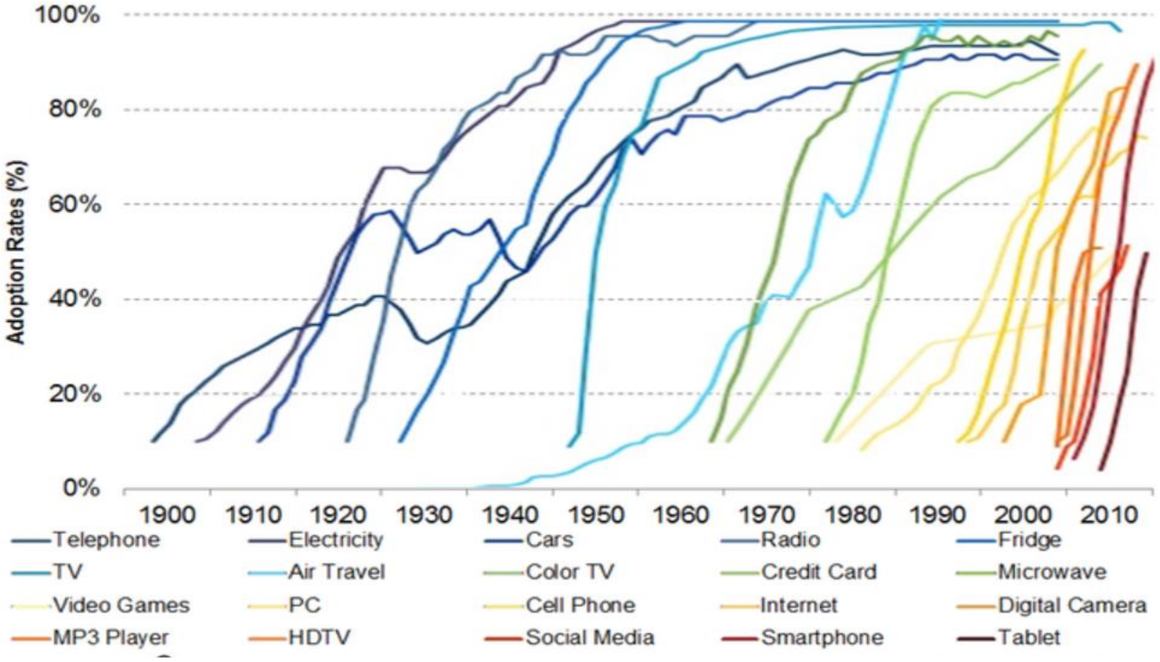
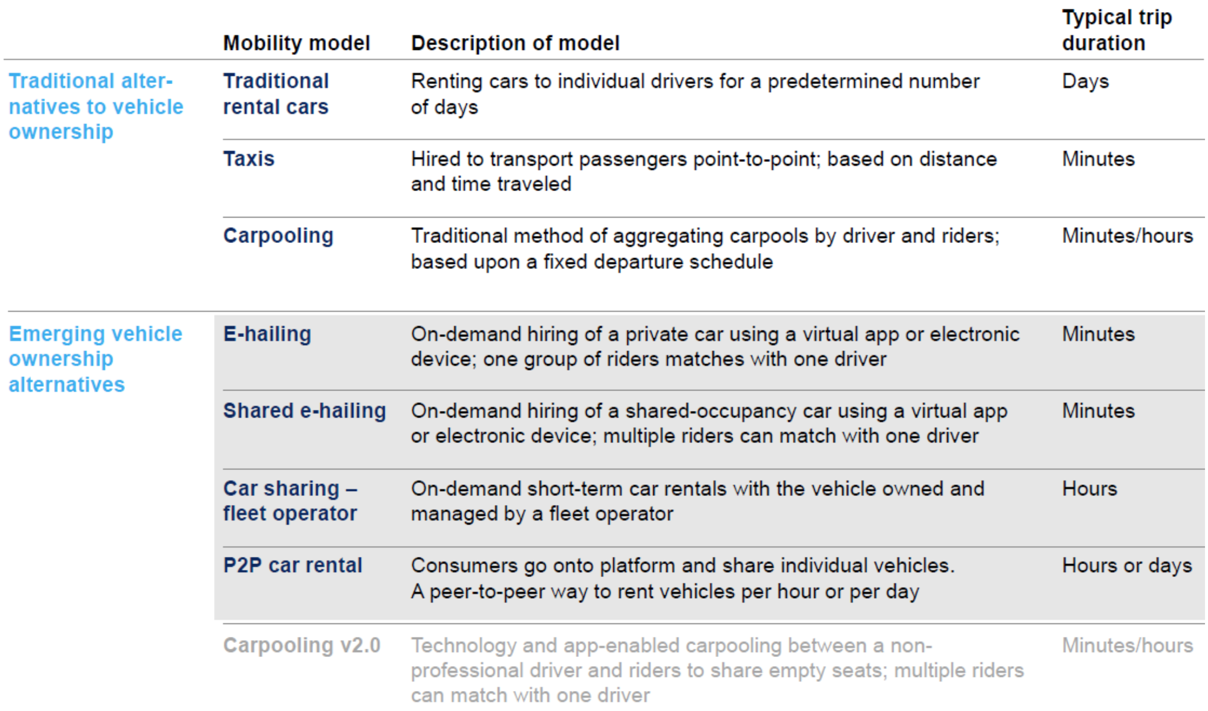


Figure 28. Adoption of technology in the US. Source: Dediu (2013)

6.1. Electric powertrains and new automotive business models

The mobility sector is facing a change regarding how people consume their transportation needs. *Table 18* illustrate some of these and automakers of BEV and FCEV must understand that while until recently cars were seen as a sign of status, this does not seem to be the case anymore. As a result, it is forecasted that mobility as a service (MaaS) will change how the automotive market operates moving towards servidisation. While much marketing was typically oriented towards drivers, with the new paradigm shift, the end customer may well be the large fleet operator. Reliability and utilisation rates are likely to be key selling points, as these vehicles may need to be available 24x7. As such, vehicles built to be easily and quickly maintained, serviced and fixed will be more successful. BEV and FCEV have an advantage versus conventional cars as they have simpler powertrains and gearboxes and do not require oil and air filter changes. Toyota (2017) indicated that the company is very interested in promoting contract hire, rather than straight purchases due to the high residual value of FCEV at the end of the leasing period due to low very low tear and wear of this technology.

Table 18. Automakers can sell EVs in a range of alternative mobility models. Grey cells represent the business models that can improve EV economics. Source: Knupfer et al. (2017).



	Mobility model	Description of model	Typical trip duration
Traditional alternatives to vehicle ownership	Traditional rental cars	Renting cars to individual drivers for a predetermined number of days	Days
	Taxis	Hired to transport passengers point-to-point; based on distance and time traveled	Minutes
	Carpooling	Traditional method of aggregating carpools by driver and riders; based upon a fixed departure schedule	Minutes/hours
Emerging vehicle ownership alternatives	E-hailing	On-demand hiring of a private car using a virtual app or electronic device; one group of riders matches with one driver	Minutes
	Shared e-hailing	On-demand hiring of a shared-occupancy car using a virtual app or electronic device; multiple riders can match with one driver	Minutes
	Car sharing – fleet operator	On-demand short-term car rentals with the vehicle owned and managed by a fleet operator	Hours
	P2P car rental	Consumers go onto platform and share individual vehicles. A peer-to-peer way to rent vehicles per hour or per day	Hours or days
	Carpooling v2.0	Technology and app-enabled carpooling between a non-professional driver and riders to share empty seats; multiple riders can match with one driver	Minutes/hours

However, the limited range of BEV is likely to be problematic. To overcome this, in addition to technological breakthroughs alternative solutions could offer new business opportunities (e.g. fast battery swapping service providers). BEV and FCEV manufacturers must be aware of this MaaS trend to ascertain that their vehicles are prepared and suitable for these changes on vehicle ownership and their technical requirements (e.g. very high utilisation rates). Automakers only producing BEV will be more vulnerable and reliant on disruptive innovation in battery technology (e.g. by enabling faster recharging times) than those also producing FCEV.

Another upcoming trend is the arrival of connected autonomous vehicles (CAV). This is likely to have a massive impact on business models and they will be able to operate under any of the MaaS models. With the current tax framework, corporative buyers can claim the costs of their investments against taxable profits (First Year Allowances). As a result, fleet operators might seem less sensitive towards price. However, as there is less scope for differentiation among CAV (vehicles will always respect speed limits and will drive efficiently avoiding harsh acceleration and braking) the massive purchasing power fleet operators will force automakers to compete very aggressively to reduce costs and provide further differentiation. This presents an opportunity for vehicle manufacturers to invest in CAV technologies and vertically integrate with MaaS providers via mergers, acquisitions or strategic alliances. Higher availability at short notice seems to provide an advantage to FCEV against BEV but this could be challenged if new technological breakthroughs could improve battery recharging time and higher energy density.

6.1. Unique Selling Points: Trip distances and recharging time

The average annual driven by diesel cars is around 11,200 miles (DfT, 2016d), which is under 31 miles per day. The average trip length driven by cars in Great Britain is around 8.4 miles (DfT, 2016a). Furthermore, 99.32% of all the trips done by people are shorter than 100 miles (DfT, 2016b). From all the trips driven by cars, just 3 per year are longer than 100 miles (DfT, 2016c), this is a mere 0.63% of all trips. Assuming that almost 94% of drivers' trips are 25 miles or shorter, 93% of people could recharge their batteries during the weekend only, as long as their cars are fitted with a 60 kWh battery. Statistic details appear in Appendix XX. This means that for most people most of the time BEV provide enough range, as long as they recharge their vehicles once a day (typically overnight). Therefore, range for private customers at least, is not as critical as most people think. Nevertheless, recharging once a week is likely to be a differentiation factor between BEVs. BEV have a range between 59 and 248 miles. The map illustrated in *Figure 29* represents the range for a vehicle departing from Manchester. The inner circle represents the round trip distance that the BEV with the shortest range (i-MIEV) can do, assuming that departs fully charged. The second circle represents the maximum round trip distance that some of the vehicles with most range could do (Tesla Model X and Opel Ampera-e). The third circle, illustrates the distance that the same vehicles could cover if they would recharge at the destination point (1 way trip). ICE and FCEV offer a much better range, and with the right hydrogen-refuelling infrastructure, range anxiety should not be a problem. Unfortunately, in the UK, there are just 15 HRS operative (hydrogen refuelling stations) and five more planned, as illustrated in Figure *30*. This is a factor that unless solved will limit the penetration of FCEV in the market.

Figure 29. Range of distances from Manchester. Adapted from: Google (2017)

Figure 30. Map of UK hydrogen refuelling stations. Source:H2stations.org (2017)

Another of the key differences between BEV and FCEV is recharging time. Private consumers of BEV can potentially wait to recharge overnight (as they normally do with their mobile phones). If waiting time is not a problem, BEV cost half the price of a FCEV and offer enough range for most trips. In contrast, fleet operators may see this as a weakness as these long recharging times could limit vehicles' availability and decreasing utilisation rates. It is possible to recharge 80% of a battery in one hour, the time typically used to clean a rental car before giving it to a new customer. However, this would require a large number of fast superchargers. To give an idea of the recharging times and costs that this entails Table *19* includes some of the fundamental details. Potentially, some installations with chargers over 22 kW are likely to require civil and remedial work if the local low voltage network wiring is not prepared to cope with the increase on load demand. This can increase the costs even further. Therefore, despite that is technically feasible to recharge a BEV in less than an hour, there is a trade-off between cost and recharging time. Furthermore, recharging points with more than one socket share the available power, which leads to longer recharging times. The disruption due to recharging time can be mitigated to some extent by managing recharging schedules but in a fleet where all vehicles are electric, keeping high levels of vehicle utilisation may prove very challenging.

Table 19. Recharging times according to charging point power and cost of each unit.

Characteristics charger					**Size of the battery (kWh)**			**Retail price**
					60	**75**	**90**	
Voltage (input)		**A**	**P**	**kW**	**Recharging time (hr : min)**			**(£)**
VAC	230	16	1	3.7	16:18	20:22	24:27	779
	230	16	3	11	05:27	06:49	08:10	1,008
	230	32	1	7.4	08:09	10:11	12:13	854
	230	32	3	22.1	02:43	03:23	04:04	1,105
	230	63	3	43.5	01:22	01:43	02:04	2,000
VDC	400	125	1	50	01:12	01:30	01:48	19,000
	400	300	1	120	00:30	00:37	00:45	105,000
	500	700	1	350	00:10	00:12	00:15	N/A

In contrast, FCEV recharging time is less than a minute per kg of hydrogen, and as fuel tanks contain just around 5 kg (at 70 MPa) it takes 3-5 minutes to refuel, a similar time as conventional ICEV. Besides, these cars will be able to refuel in refuelling stations funded by oil or hydrogen companies, not by the end user or consumer. It can be argued that this is also the case for VDC superchargers, but the difference is that there is a cost associated to the value of the time lost while recharging must be paid by someone, as it is not always possible to use this waiting time productively. Moreover, in the case studies here presented, if the companies do not have a superfast recharger, recharging waiting time is likely to affect the annual mileage that those vehicles could potentially do, limiting the type of service that they can offer and revenues.

6.2. Power capacity constraints

According to OICA (2016), there were 32.6 million cars in use in the UK in 2014. Assuming that all vehicles would become BEV by 2040, the results of the FES model indicate that the grid would need an extra 21.9 GW of electricity. This is the equivalent of almost 7 Hinkley Point C nuclear power stations. Considering the time taken to tender, study, approve and build these types of plants, and the cost that they represent for the taxpayer, it seems that the capacity of the national grid may become a constraint for BEV sales. Alternatively, renewables could be deployed, however, the only way of avoiding over dimensioning capacity is using energy storage. One of the ways of doing this is by converting the electricity into hydrogen, storing it in salt caverns, and convert it again into electricity. In that case, using hydrogen to power vehicles could be a good alternative, to avoid conversion inefficiencies. FCEV are not constrained by the national grid. As long as there is enough natural gas or coal, SMR and coal gasification plants can produce hydrogen that when combined with CCS can yield low GHG emissions. Alternatively, as previously mentioned, hydrogen can be produced from excess renewables.

As presented in Chapter 1, hydrogen production for vehicles is negligible and to generate the levels required to substitute petrol and diesel, requires the use of natural gas (another fossil fuel) and CCS in a first stage. Over time, green (produced from renewables) and low carbon hydrogen (hydrogen produced from nuclear) will contribute to reduce the well-to-tank GHG footprint of FCEV.

7. Conclusions

Governments are interested in BEV and FCEV because these can contribute to energy security by reducing the reliance on foreign supplies of fossil fuels. Furthermore, they present several pathways that can help to meet national decarbonisation goals for transport as well as Climate Change agreements. Local authorities are also interested as electric powertrains can reduce human health problems related to air quality produced by conventional cars. Private consumers are also interested because these vehicles present very low operational costs and high power performance. These are some of the key conclusions and messages from this research:

- These are some the most pressing challenges that automakers must consider in their **strategy** propositions:
    - In the near future, CAV and MaaS will offer less scope for powertrain differentiation. Typically, the main customers that automakers target are private drivers but soon with newer changes in mobility services these might be large fleet operators.
    - The needs of private and corporate consumers are different and different strategies should be developed for each segment. For example, fleet operators are likely to value reliability and the capability to hold high utilisation rates of their vehicles.
    - Focus regarding electric powertrains must be on improving energy density of batteries and hydrogen tanks.
    - The main issue with FCEV is their cost. This limits the market to people who need long ranges or cannot wait for hours to get their vehicles operational.
    - The main problem with BEV is the shorter range and long recharging time. However, range is improving and catching up with FCEV. For most users, most of the time, range anxiety should not be a problem if they are willing to recharge overnight. Unless recharging time of BEV is reduced, those vehicles are unlikely to be used in large annual mileage operations, which may limit its market segment. Improving performance in these areas is likely to provide a competitive advantage.

  - BEV are cheaper than FCEV but much more expensive than ICE. Reducing battery costs is critical to popularise the technology.
  - Battery production capabilities are being deployed by many manufacturers. Automakers should consider having very close relationships with battery makers to guarantee a stable stream of batteries supply.
  - There is scope for creating partnerships to deploy the recharging and refuelling infrastructure, as this will enable higher sales.
  - Economies of scale and learning curves are critical to reduce the costs of both technologies. Forecasts expect price FCEV to be marginally more expensive than BEV by 2030 and to reach parity with ICE by 2050.
  - All automakers are engaged in electric powertrain development. However, a survey among directors of these companies shows that they FCEV as the real breakthrough in electric mobility.
  - Residual value from FCEV is likely to be very high compared to BEV as there is little tear and wear and FCEV do not suffer from a considerable degradation of the fuel cell. This motivates automakers to lease these vehicles as they can obtain a high resale value at the end of the contract or lease again.
  - The way of financing the procurement of BEV and FCEV and length of the contract makes a big difference, partly due to the relevance of the residual values of the vehicles at the end of the contracts.
- The production of electric powertrains presents several **constraining factors** that might jeopardise the productivity of automakers.
  - Materials could limit penetration of BEV and FCEV.
    Limitations regarding Li production and existing worldwide reserves constrain the amount of vehicles that can be produced nowadays to 5.5% of current global levels. Platinum would allow 10% of the annual production. None of these resources are renewable and despite recycling, these technologies are not sustainable in the long run. However, new battery chemistries could overcome the recharging time and the dependence on Lithium, as well as improve energy density. If this would happen, BEV would displace FCEV in all markets. Other materials are

  also a cause of concern among automakers as they are controlled by a small number of foreign powers (e.g. cobalt, rare earths).
  - The planned battery production capacity by 2020 could supply just 2.5 million vehicles (with large batteries).
  - The low voltage network infrastructure will need to be upgraded in some areas.
  - BEV will increase the demand for electricity putting more stress on the national grid in a time when older power stations are being decommissioned.
  - There are not enough superfast rechargers. Furthermore, not everybody lives in a house and has a recharging socket at the kerb side. People living in flats, might struggle to find recharging points.
  - There is not enough hydrogen production capacity either.

There are too few hydrogen refuelling stations to offer an acceptable level of service.

- These are some of the **environmental factors** to consider:
  - Both technologies produce zero emissions at the point of use and very low noise levels. This can contribute to improve human health.
  - By 2050 due to the decarbonisation of the grid, WTW emissions from BEV could be minimal. Embedded emissions from vehicle manufacturing will still be several tones per car.
  - WTW GHG emissions from FCEV are likely to be very high, unless hydrogen production is coupled to carbon capture and storage technologies or a green hydrogen standard is accepted.
  - There might be scope for both technologies to co-exist, as hydrogen could be used to store the surplus of energy generated by renewables and overcome their intermittent production patterns.
  - The same as there are guarantees of origin for renewable electricity, a green hydrogen standard could improve customer choice and enable consumers to minimise their WTW GHG emissions.
  - Recycling lithium is not cost effective and current recycling levels are low.
- The success of electric vehicles will have other direct and **indirect impacts** in different sectors of the economy and the exchequer.

  - FCEV offer a transition pathway for oil companies towards the hydrogen economy within the boundaries of their current business models.
  - The future of BEV might be closely linked to the success of energy management technologies. To mitigate the stress on power demand, a system will be necessary to influence charging profiles of BEV.
  - Smart grids can benefit from electric powertrains by using vehicle-to-grid technologies that could contribute to balance the grid and improve the quality of power.
  - As these vehicles require less maintenance and have fewer technical problems, workshops will have lower workloads.
  - With the right infrastructure, utility companies are likely to be the great beneficiaries if BEV succeed. Randall (2016) forecasts that electric cars will cause the next oil crisis; with the current annual growth rate (60%), electric cars will displace 2 million barrels of oil per day by 2023. This is likely to require the deployment of CCS technologies, as most of the hydrogen will be generated from methane in a first stage.
  - Both technologies improve national energy security by providing several energy pathways with multiple feedstocks that can be used to produce electricity and hydrogen. Both energy carriers can support each other via Power-to-gas and gas-to-power technologies.
  - MOT should become cheaper, as there are not exhaust emissions to analyse.
  - The exchequer will receive lower income from ICEV and once EV achieve high penetration levels will have to define new taxation mechanisms.
  - Alternative powertrains present a good business opportunity for the UK that fits within the national industrial strategy.

Currently, UK policy lacks clear targets in regards to the percentage of the national fleet that BEV and FCEV should represent. Similarly, there is no commitment regarding the funding for refuelling and recharging infrastructure, beyond the grants provided every now and then by OLEV. The UK has a technology neutral approach towards energy policy but without long-term targets and funding commitments, the uptake of these technologies is likely to be very slow. Furthermore, a review of the policy landscape has demonstrated that current energy policy instruments do not include hydrogen to the same extent as electricity. This may be the case because FCEV and BEV were seen as very long-term alternatives to ICEV. However, the shift toward cleaner air, innovations and economies of scale have brought to markets these technologies at a much faster rate than expected. An effort should be made to create a true level playing field, as FCEV and BEV are no longer futuristic alternatives, they are here now and commercially available.

7.1. Suggestions for further research

This research has calculated lifecycle GHG emissions of BEV and FCEV. Presenting TTW air quality emissions would be an interesting addition to this study. Adding the social costs of GHG and air quality pollution avoided with these powertrains and compared these to ICEV, would provide a fair comparison of the true total costs of these technologies.

An exhaustive analysis of the UK industrial capacity via a model similar to the UK TIMES model, could provide further details regarding how much hydrogen capacity should and could be built, to enable full deployment of FCEV by 2050.

The author encourages other researchers to conduct a wide survey of the characteristics of low voltage networks to ascertain the costs of adapting local grids to cope with the surge in power demand from BEV.

7.2. Limitations of this research and reflections on the challenges found

Some very popular vehicle models in the EU were excluded from this study as not reliable fuel economy under the EPA driving cycle was found. Repeating this study, including those models and using the energy consumption from the new World Harmonised Driving Cycle or a more realistic driving cycle would improve the accuracy of the calculations for case study 1, as companies from case studies 2 and 3 do not pay the fuel operating costs.

One of the limitations of this study was the reliance on the GREET model which focuses on industrial processes and carbon intensities of US energy systems. The embedded carbon emissions of BEV and FCEV are likely to differ to some extent to those of vehicles produced in the UK. The alternative of using Ecoinvent was even worse because some of the lack of granularity, as many of its pathways are based in

Switzerland and there is not scope for configure the technical characteristics of the vehicles.

This study was inspired in the case study of a few organisations. Therefore operational details might not represent the sector in which these companies operate. A survey among a large sample would have been ideal but the reality is that there are just three large scale FCEV manufacturers worldwide and just a handful of customers in the UK.

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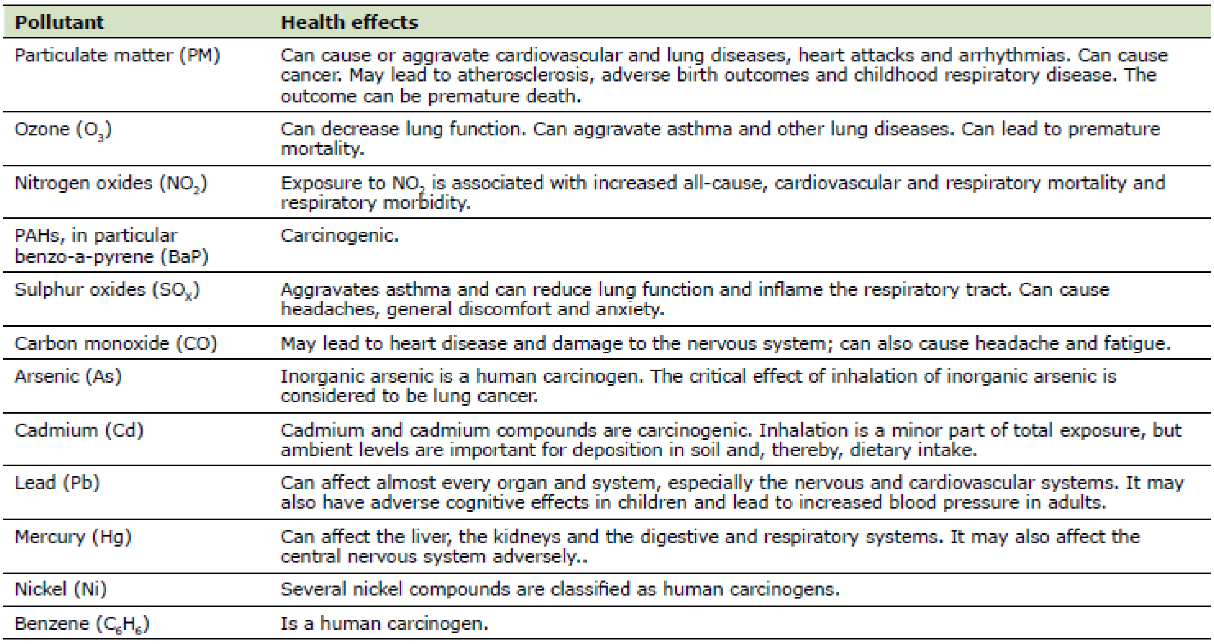
Appendices

Appendix I – Impact of Air Pollutants on Human Health

Table 20. Effects on human health of air pollutants in outdoor air. Source: EEA (2014).



Pollutant	Health effects
Particulate matter (PM)	Can cause or aggravate cardiovascular and lung diseases, heart attacks and arrhythmias. Can cause cancer. May lead to atherosclerosis, adverse birth outcomes and childhood respiratory disease. The outcome can be premature death.
Ozone (O_3)	Can decrease lung function. Can aggravate asthma and other lung diseases. Can lead to premature mortality.
Nitrogen oxides (NO_2)	Exposure to NO_2 is associated with increased all-cause, cardiovascular and respiratory mortality and respiratory morbidity.
PAHs, in particular benzo-a-pyrene (BaP)	Carcinogenic.
Sulphur oxides (SO_x)	Aggravates asthma and can reduce lung function and inflame the respiratory tract. Can cause headaches, general discomfort and anxiety.
Carbon monoxide (CO)	May lead to heart disease and damage to the nervous system; can also cause headache and fatigue.
Arsenic (As)	Inorganic arsenic is a human carcinogen. The critical effect of inhalation of inorganic arsenic is considered to be lung cancer.
Cadmium (Cd)	Cadmium and cadmium compounds are carcinogenic. Inhalation is a minor part of total exposure, but ambient levels are important for deposition in soil and, thereby, dietary intake.
Lead (Pb)	Can affect almost every organ and system, especially the nervous and cardiovascular systems. It may also have adverse cognitive effects in children and lead to increased blood pressure in adults.
Mercury (Hg)	Can affect the liver, the kidneys and the digestive and respiratory systems. It may also affect the central nervous system adversely..
Nickel (Ni)	Several nickel compounds are classified as human carcinogens.
Benzene (C_6H_6)	Is a human carcinogen.

Appendix II– Porter's Generic Strategies

The Table below applies the strategic positioning model developed by Porter in the context of electric vehicle manufacturers.

		Competitive Advantage	
		Lower Cost	Differentiation
Competitive Focus	Broad Target	**Cost Leadership** Ford, GM, Nissan, Volkswagen BEV	**Differentiation** Mercedes, BMW BEV Honda, Toyota, Hyundai FCEV (Tesla Model 3)
	Narrow Customer Segment	**Cost Focus** Smart BEV	**Differentiation Focus** Tesla BEV

Figure 31. Three generic strategies applied to BEV and FCEV brands.

Tesla, for example, positions itself upmarket providing differentiation focus in regards to vehicle performance (e.g. highest power, dual motors, faster charging times) and exclusive services (it owns a worldwide proprietary superfast recharging infrastructure at prime locations). However, to consolidate profits, the company must generate more revenue and for this reason is changing strategy and shifting towards a simple differentiation. By achieving economies of scale and implementing new production processes, Tesla aims at broadening the customer base with the introduction of the new Tesla 3, a much cheaper vehicle than the Model S or Model X. With this move the company can increase sales and thanks to their differentiated features (such as autopilot, good vehicle range) and services (access to Supercharger stations and free recharging allowance) they can avoid strategies aiming at becoming cost leaders, as competition on that area tends to result in lower profitability. Smart for example produces very tinny cars (e.g. 2 seats) focused on a very particular type of consumer (e.g. typically urban) and it is capable to offer very cheap prices. FCEV automakers cannot compete in price at the moment and the only differentiation that they can offer is longer vehicle range and faster refuelling. In the USA, two of these offer free refuelling with leasing contracts, which differentiate them from most BEV makers and reduces operating costs for the customers. Manufacturers such as Daimler and BMW operate differentiation strategies that have allowed these brands to charge a premium for their vehicles. In the sample studied, the Mercedes 250e was more expensive BEV after the Tesla models, despite having a battery less than half of an Opel Ampera-e. So, if customers value range, Mercedes is not delivering it, and their strategic positioning doesn’t fit with the characteristics of this model. GM with the new Chevrolet Bolt (known in the EU as Opel Ampera-e) offers differentiation by combining moderate prices with one of the biggest batteries in the market. The company could charge a premium as the price differential with Tesla is almost £30,000. The Honda, Toyota and Hyundai models offer differentiation because they are the only brands producing FCEV, hence with very large range and almost instantaneous refuelling. The other brands of BEV offer similar performance and their strategies have to focus on achieving cost leadership. Volkswagen has expertise in producing reliable and economic vehicles. However, it can adjust its competitive strategy depending on the different strategic business unit (brands). This means that they can develop a cost leadership with Seat and Skoda, while defining differentiated strategy with Audi and a differentiated focus with Porsche and Bentley.

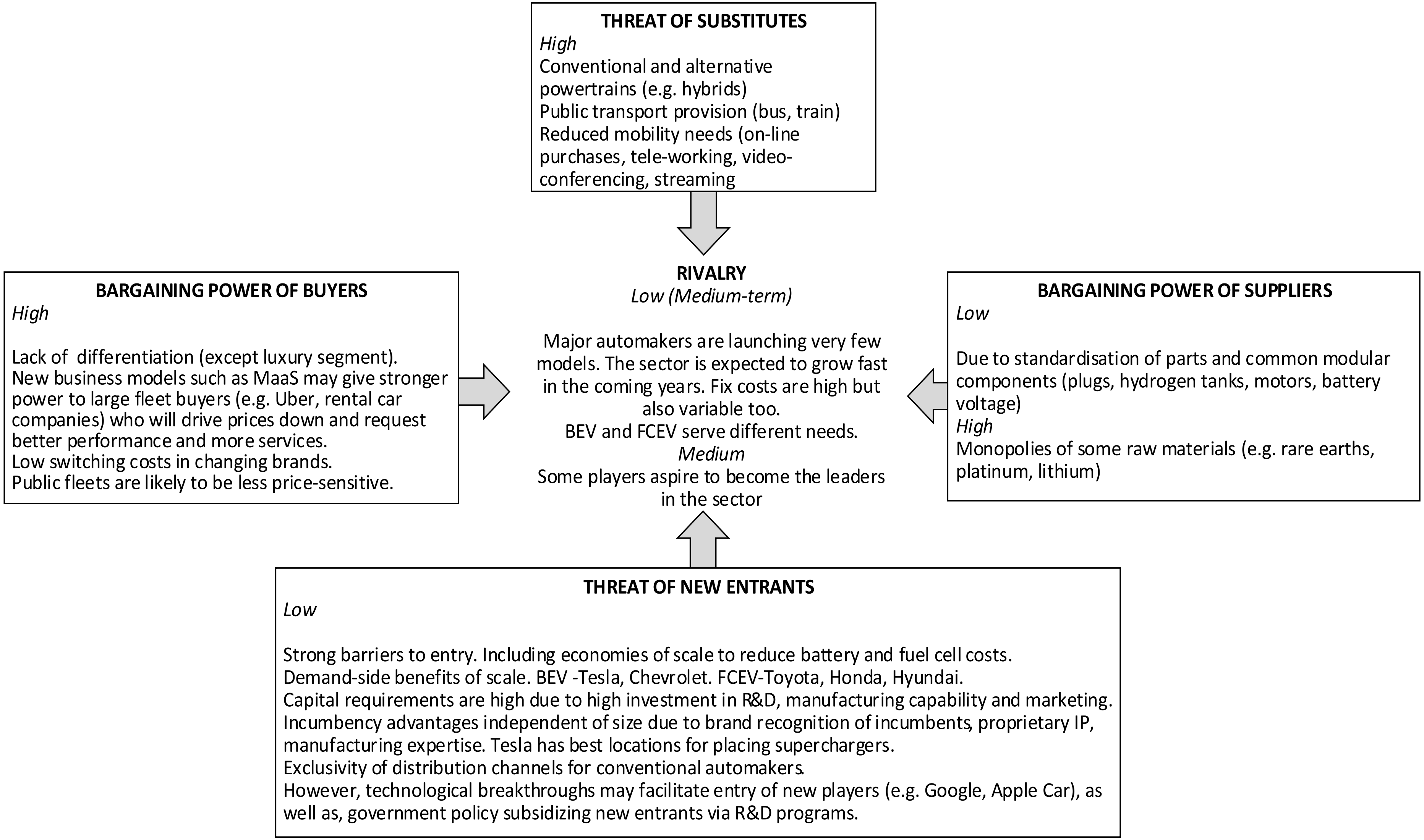
Autonomous driving might commoditise vehicles and there might be less scope for differentiation (aside of the comfort of seats or infotainment systems such as IOS Apple Carplay vs. Android Auto). To retain differentiation companies might need to develop considerable technological breakthroughs or provide exclusive services. The car sharing trend might facilitate the move of some automakers from cost leadership to cost focus, targeting large fleet companies.

Appendix III – Porter's Five Forces applied model

Manufacturing BEV and FCEV is a good business opportunity because there rivalry from competitors is low, as not all companies are considering developing these powertrains in exclusive and ditching ICEVs. Besides, the treat from new entrants is also low, as building a production plants requires considerable capital (meaning by new, companies that do not produce any type of vehicles nowadays). Furthermore, automakers have a very strong bargaining power when negotiating with suppliers, due to their massive volume of purchases. Developing expertise in this area now, at the beginning of this technological change offers them better future prospects, first by being one of the first entrants in the markets (and the advantages that this comprises) and also it hedge risks against potential changes in environmental policy that may end banning and phasing out petrol and diesel vehicles.

Porter (2008) recommends to position the company where the forces are weakest. For example, rental companies can own very large fleets. Minimising capital expenses is critical for those companies while operating expenses are less relevant because their customers (drivers) bear those costs (insurance premiums and fuel costs). Because these fleets can combine different powertrains, including ICEV, this gives these companies a very strong bargaining power and unless BEV and FCEV have similar capital costs to ICEV they will not buy them, beyond the units procured via grants, subsidies and in the context of demonstration projects.

To provide a long-term business model, automakers could to focus on a customer group where competitive forces are weaker. For example, public fleets making a policy statement regarding low carbon and low air quality pollution emissions, as these are less cost sensitive. Also, in the absence of policy mandates, such as the ones found in the USA where public fleets are obliged to spend a % of their annual budget in procuring alternative powertrain vehicles, automakers targeting the private buyer might be more successful as this has a lower bargaining power and some customers may buy this vehicles due to their emotional connections with environmentally friendly products.



THREAT OF SUBSTITUTES
High
Conventional and alternative powertrains (e.g. hybrids)
Public transport provision (bus, train)
Reduced mobility needs (on-line purchases, tele-working, video-conferencing, streaming

BARGAINING POWER OF BUYERS
High

Lack of differentiation (except luxury segment).
New business models such as MaaS may give stronger power to large fleet buyers (e.g. Uber, rental car companies) who will drive prices down and request better performance and more services.
Low switching costs in changing brands.
Public fleets are likely to be less price-sensitive.

RIVALRY
Low (Medium-term)

Major automakers are launching very few models. The sector is expected to grow fast in the coming years. Fix costs are high but also variable too.
BEV and FCEV serve different needs.
Medium
Some players aspire to become the leaders in the sector

BARGAINING POWER OF SUPPLIERS
Low

Due to standardisation of parts and common modular components (plugs, hydrogen tanks, motors, battery voltage)
High
Monopolies of some raw materials (e.g. rare earths, platinum, lithium)

THREAT OF NEW ENTRANTS
Low

Strong barriers to entry. Including economies of scale to reduce battery and fuel cell costs.
Demand-side benefits of scale. BEV -Tesla, Chevrolet. FCEV-Toyota, Honda, Hyundai.
Capital requirements are high due to high investment in R&D, manufacturing capability and marketing.
Incumbency advantages independent of size due to brand recognition of incumbents, proprietary IP, manufacturing expertise. Tesla has best locations for placing superchargers.
Exclusivity of distribution channels for conventional automakers.
However, technological breakthroughs may facilitate entry of new players (e.g. Google, Apple Car), as well as, government policy subsidizing new entrants via R&D programs.

Figure 32. Five Forces analysis of the electric vehicle sector.

Appendix IV – Swot Analysis Electric Cars Business

Table 21. SWOT analysis electric powertrain vehicles.

Strengths
Zero GHG and air quality emissions at the point of use and potentially low WTW GHG pathways Quiet at low speeds Very low maintenance costs (no oil, air filters, exhaust catalyst and sensors, low tear and wear beyond tires) High reliability (fewer moving parts: engine, simpler gearbox) Diversity of feedstocks to produce energy contributes to provide energy security Diversity of production methods provides flexibility Advantageous taxation Lower embedded GHG emissions
Weaknesses
Poor sales result in low economies of scale and learning rates, which in turn slow down cost reductions. This damages sales. Poor infrastructure due to poor sales. Poor sales due to poor infrastructure. Vehicles are much more expensive than incumbent technology (total cost of ownership)
Opportunities
More stringent policies regarding air quality emission favour electric powertrain vehicles Considerable potential for process and product innovation Due to vehicle-to-grid technologies and smart grids, these vehicles can become distributed generators. This can have value to balance the grid and also to provide power to households in case of emergency (e.g. blackouts) Potential for massive cost reductions once sales reach hundreds of thousands of vehicles. By 2030, these vehicles will be marginally more expensive than ICE cars (excluding the cost of externalities). By 2050, they are expected to become cheaper than those. Currently, in the UK zero emission cars benefit from a subsidy of £4,500/unit. These vehicles are exempt from the London congestion zone charge. Local incentives such as free parking are decided at local level. Electric vehicles (BEV/FCEV) pay reduced company car tax rates. There is potential to develop BEV/FCEV hybrids (range extenders)
Threats
Reduced R&D public funding (e.g. Brexit & Horizon 2020) Change regarding technology neutrality policy, UK Government in favour of one specific technology (e.g. favouring BEVs vs. FCEV or other powertrain technologies vs. electric cars) Policy uncertainty regarding policy instruments and regulations Lack of infrastructure and mandatory vehicle penetration targets suggest a weak commitment from the UK Government towards BEV and FCEV Vehicle designs could reduce vehicle payload (e.g. some vehicles have 4 seats instead of 5) Electric cars rely on scarce raw materials such as rare earths controlled by foreign countries. Emergence of “new players” from China, South Korea and India.

Appendix V – Swot Analysis BEV Business

Table 22. SWOT analysis BEV.

Strengths
High performance (torque, speed, acceleration) Very low cost per kilometre (full battery ~£3/22 kWh) Convenience. Some dwellers can recharge vehicle at home High TTW efficiency Highest WTW efficiency pathways Lowest GHG/air quality pathways
Weaknesses
Short range and long recharging times Poor fast recharging infrastructure High capital cost supercharging stations Air conditioning / heating reduces vehicle range considerably Poor residual values due to battery degradation
Opportunities
Most models are exempt from paying VED (road tax) New battery chemistry, could improve energy density and recharging times Company Tax Benefits: Tax benefits for businesses installing charging infrastructure through a 100% first year allowance (FYA) for expenditure incurred on electric vehicle charge point equipment. Offers opportunity to utilities to enter new market Infrastructure Incentives: £500 incentive for installing a dedicated home charging station. Infrastructure Incentives: £300 per socket towards the installation of a workplace charge point for employee and fleets. Infrastructure Incentives: Up to 75% (capped at £7500) towards the cost of installing an on-street residential charge point in areas without off-street parking. Generation costs of electricity via renewables are becoming cheaper than conventional methods. Empowerment of guarantees of origin certificates for green electricity
Threats
Breakthroughs from fuel cell (e.g. faster power transfer) and fuel storage innovation Standardisation vs. proprietary recharging connections National grid requires extra capacity Low voltage networks may need adaptation Use of renewables may require deployment of energy storage technologies (e.g. large batteries or hydrogen reservoirs) Most Lithium reserves are located among 6 countries Dependency of lithium is not sustainable due to limited reserves Performance is affected by extreme temperatures Fast charging / short cycles can damage batteries Lack of harmonisation of quality, safety and engineering standards (e.g. BSI ISO recharging plugs, voltage, amperage, etc.). Changes in policy instruments supporting the production of low carbon power (e.g. Feed-in-tariffs, Contracts for Difference, etc.).

Appendix VI – Swot Analysis FCEV Business

Table 23. SWOT analysis FCEV.

Strengths
Long range Fast refuelling Allows the use of air conditioning without compromising range. Similar user experience as conventional cars
Weaknesses
Higher procurement costs than BEV Poorer refuelling infrastructure than BEV High capital cost hydrogen refuelling stations Lower WTW energy efficiency than BEV
Opportunities
New guidelines allowing co-location HRS with conventional pumps will decrease capital costs New catalysts could decrease costs of fuel cells New storage vectors and higher volumetric energy densities Possibility to improve instant torque Potential to improve power density fuel cells Role of different FC types such as SOFC in combination with biofuels Support large corporations via the Hydrogen Council (vehicle manufacturers, oil and energy companies, gas distributors) Contribution to energy security: diversity, flexibility, synergies with other energy systems (heating and power sectors). Synergies offer a soft transition to oil companies to reduce reliance on fossil fuels A green hydrogen standard can generate very low carbon pathways Extend technology to heavy-duty vehicles (e.g. HGVs, refuse trucks, long distance coaches, and off-road vehicles such as farm tractors, mining vehicles) plus other transport modes such as trains, trams and ships. Inclusion of hydrogen as a renewable fuel of non-biological origin in the Renewable Transport Fuel Certificates Storage of liquid hydrogen produces boiling-off (1% leakages daily). Recovery is recommended when possible. Possibility for a Guarantee of Origin market for green hydrogen Capable Combination with e-mobility models: car sharing, pooling, clubs, etc.
Threats
Breakthroughs from battery technology innovation As models cost over £40,000 they have to pay VED for 5 years NIMBY attitudes towards HRS deployment Customers' acceptance of hydrogen as a fuel for transportation (safety) Lack of harmonisation of green hydrogen standard Production of hydrogen at large scale require fossil fuels and CCS in the short-term to yield low GHG emissions Inefficient delivery and transformation systems (liquefaction, transportation) Except electrolysis, most production pathways require complex filtration/purification systems Production costs of green hydrogen are expensive Most platinum reserves are located in South Africa

Due to slow reaction time of FC, FCEV still require (small) batteries Lack of worldwide harmonisation of quality, safety and engineering standards (e.g. BSI ISO pressure, nozzle shapes, etc.) Hydrogen is not included in national energy roadmaps and it is not explicit in most policy instruments There is not enough hydrogen production capability right now to power scenarios with 100% FCEV

Appendix VII – PESTLE Analysis BEV Businesses

The political and legal environment, for example, can help companies to identify future market changes. BEV and FCEV compete with a consolidated incumbent technology (ICEV) that provide longer range, convenient and widely available refuelling infrastructure, with well-developed supply chains and at a much cheaper TCO. A limited view would suggest that investing on electric powertrain vehicles is not a wise strategy. However, due to policy and societal changes, dependence on ICE sales could become a liability in the near future as many cities around the world are planning to ban polluting vehicles. As a result, there is an opportunity for conventional vehicle manufacturers to adapt and for new entrants to position themselves in this space.

Table 24. PESTLE analysis to be considered by BEV and FCEV manufacturers.

Political
There must be a political will to commit to long-term environmental policy certainty at a global (e.g. climate change) and local (e.g. Air quality management areas) level. A summary of policies that affect electric vehicles is shown in *Table 25*.
Economic
Funding must be made available to quick start recharging and hydrogen refuelling infrastructure. High grow rates can also support private investment in innovative companies operating in the sector, as well as other members of their respective supply chains. A detailed summary of public funding and medium-term targets in regards to FCEV and HRS is illustrated in *Table 26*.
Social
Society should engage with cleaner modes of transport to reduce air quality and GHG emissions and focus on reducing externalities from transport. NIMBY attitudes regarding hydrogen refuelling infrastructure should be avoided, as well as opposition to wind farms, as these contribute to one of the lower carbon emission electricity and electrolytic hydrogen generation pathways.
Technological
Consumers must embrace low carbon technology powertrains. Investments on R&D are critical to deliver the breakthroughs on battery energy density and reducing recharging times necessary to deliver an experience similar to the one offered by FCEV or ICE. Similarly, R&D on catalyst and energy storage will benefit FCEVs technologies. Vehicles should offer similar guarantee and reliability as ICE vehicles.
Legal
Standards (plug sockets and chargers), refuelling nozzles and hydrogen quality will be necessary for increasing customer base. Safety standards also important to reassure the public.
Environmental
Automakers should be aware of the environmental agreements of the international community as this can give clues regarding future technological limitations (e.g. air quality directives, climate change goals)

Appendix VIII – Policies applicable to electric cars

Table 25. Example of policies to be aware of when operating in the electric vehicle sector.

Policy	Objective	Type of Policy	Main stakeholder	Comments
Renewable Transport Fuel Obligations (RTFO 5% - 8%)	Increase the share of renewables	Regulatory	Fuel Producers	Hydrogen will be included as a 'Renewable Fuel of Non-Biological Origin'in the Renewable Transport Obligation.
Local Sustainable Transport Fund	Economic growth / Employment	Economic	Local businesses	This scheme can promote the development of new local automotive supply chains.
FCEV Fleet Support scheme	Create a market	Economic, voluntary	Public procurement Private enterprise fleet owners/operators	This scheme provides grants for the uptake of FCEV fleets.
Road vehicle efficiencies: Car , HGV, HGV Natural Gas, PSV Fuel Efficiency, Van	Reduction of air pollutants / GHG emissions	Fiscal, regulatory, research. Voluntary/negotiated (e.g. HDVs)	Vehicle manufacturers / users	Vehicle efficiency thresholds are measured on a TTW basis, and these vehicle tailpipe emissions are zero. Indirectly, by becoming more stringent, these technologies benefit from the challenges experienced by ICE vehicles. These vehicles will meet any present and future Euro Emission Standard.
Alternative Fuels Infrastructure	Energy security	Economic, regulatory (voluntary for hydrogen)	Infrastructure owners / operators.	It sets reporting requirements for EU members pursuing the hydrogen agenda in their national policy frameworks and recommends a holistic view to allow refuelling for long distance travel around the EU when locating HRS infrastructure.
Advanced Propulsion Centre programme	Create a market	Economic, voluntary	Public procurement Private enterprise fleet owners/operators	This scheme provides funding for R&D of BEV.

Appendix IX – Governmental Targets in Regards EV and HRS

Table 26. Subsidies for FCEV and HRS and current and future deployment targets in FCEV leading markets. Sources: Acosta Iborra, Gupta, and Seissler (2016); BMVI (2016); IPHE (2015, 2016a, 2016b, 2016c, 2016d); METI (2014, 2016b, 2016c); NOW (2016a, 2016b); Rosner and Appel (2016); US DoE (2017b, 2017c).

Country	**FCEV**			**HRS**		
	Procurement Subsidy (£/unit)	**Car Sales (up to Sep/16)**	**Future Targets for cars**	**Procurement Subsidy (£/unit)**	**Installations (2016)**	**Future Targets**
Japan	£14,266/vehicle (£107M in total)	909 (3,500 Today Mirai in order book)	40,000 by 2020 200K by 2025 800k by 2030 (100 buses to be delivered for 2020 Olympic Games)	Subsidy for CAPEX / OPEX (local and central government) (£45M in total)	78	160 by 2020 420 by 2025
Germany	€3,000/BEV (NIP2 program)	103 (14 buses)	None	€350M in total (H2Mobility Germany)	22 27 (2017)	Yes, 400 by 2023 regardless of demand
China	£23,230/ vehicle £34,845 (vans) £58,075 (buses)	60 30 (vans) 40 (buses) (300 buses to be delivered in 2017 in Foshan)	None	£464,486 (200kgH_2/day)	4	No
UK	£2M in total by 2016 (OLEV) Another £23M for FCEV and infrastructure in 2017 £2.8M buses (Green Bus Fund)	42 18 (buses)	None	£5M in total (OLEV) Another £23M for FCEV and infrastructure in 2017	14	No
USA	\$8000/vehicle + \$0.5/gal H_2	331 33 (buses)	3.3M ZEV (including FCEV) by 2025 by 8 states	State grants (including O&M) (e.g. CA \$100M) Investment tax credit (30% up to \$30,000)	87	No
South Korea	£19,605	71 (in 2015	9,000 by 2020 630,000 by 2030	Incentive for installation, operation, capacity enhancement	7 (2015)	80 by 2020 520 by 2030

Appendix X – Attendance Hydrogen Industrial Event

The 'Hydrogen Event CVP - Heathrow Academy' took place on the 16TH March 2017 and it had an attendance of 80 people. FCEV were available to test outside (Toyota Mirai and Hyundai x25). I took a Toyota Mirai and it was as quiet as an electric car. The only emission from the exhaust was water. Pictures and video were also taken.

During this event there were presentations and two round tables were attendees could ask questions to the panels. The first panel included representatives from Toyota, Hyundai, Symbio, Intelligent Energy, Green Tomato Cars and ULEMCO.

I asked the panel how they felt regarding the recent announcement of supporting battery electric vehicles as the first challenge of the industrial strategy. They were not concerned at all. The representative from ULEMCO said that she had been in contact with BEIS and they had told her that the UK Government still follows a technology neutral approach and that this was just the first round of the budget and further funding will be also allocated to FCEVs. This was confirmed a few days later by the DfT with the allocation of extra funding for the uptake of hydrogen vehicles. The representative of Intelligent Energy said that investment on BEV's batteries also benefits FCEVs as both technologies are based on electric motors. Other participants supported this view. The representative of Hyundai also commented that as FCEV also contain a battery, innovation in this area is likely to benefit FCEV automakers too.

These were other interesting details:

- Symbio fits H_2 range extenders on electric vans (Renault Kangaroo). This extends the range considerably (300km); however, this solution doubles the cost of a baseline electric Kangaroo.
- ULEMCO dual fuel (diesel/hydrogen) adapted vehicles require the same maintenance as conventional diesel vehicles. This company matches the engine manufacturer guarantee and customers can also lease the vehicles.
- Hyundai confirmed that they will be mass producing FCEV by 2020. They also ensure that these vehicles are very reliable. I also got some literature and I saw that they are part of the Hydrogen Council and they presented a concept FCEV in Geneva recently.
- Simona from Hydrogen London (GLA) commented that a new 'guideline' to allow conventional refuelling stations to supply hydrogen alongside diesel or petrol pumps had just been published. This means that deployment of HRS do not require an standalone infrastructure and therefore this is likely to reduce costs considerably.

In the second panel session there were representatives from TfL, Heathrow, Commercial Group, Europcar and Green Tomato Cars. I asked TfL, Tomato and Europcar if have noticed a drop in the performance of their BEV. They said that they did not noticed any reduction in performance or range yet; however they have noticed a difference between winter and summer. The reason for not noticing any drop is likely to be that their fleets are quite new (less than 2 years) and under the warranty of the manufacturer. These were the highlights:

- TfL will receive 6 FCEV and 10 Renault Kangaroos with the Symbio range extender by May 2017. They also have 2 Mirais and 2 Hyundai ix35. One Mirai was at the event.
- Commercial Group (a sustainable logistics company) won last year the OLEV/Innovate UK funding for hydrogen vehicles and they are using the ULEMCO technology for their small trucks (1 ton payload). They consider that this project is providing a return on the investment due to the positive image that this project has given them (marketing). They complained about the lack of refuelling infrastructure and the fact that they had to do large detour to refuel, as no pumps were nearby their depots.
- Green Tomato Cars (a car rental company) provided insights regarding the driveability of their 3 Toyota Mirai. These cars drive ‘exactly the same as conventional car’ with the benefits of an electric powertrain (no noise). No issue with refuelling infrastructure, as the 5 current H_2 stations in Greater London is enough for them.
- Heathrow Airport. They have a CSR plan (Heathrow 2.0) for that includes reducing air quality and GHG emissions. They have a H2 refuelling station that they installed via EU funding and they are committed to maintain it and expand its usage. Also the will replace all cars and vans for electric vehicles by 2020.

Appendix XI – Case studies: Interviews / Follow up Questions

- Name of the Company
- Name and position of the respondent
- Is your company a manufacturer or consumer of FCEV?
- Do you think that BEV and FCEV are better suited for different types of operations?

Manufacturers’ specific questions

- What is the retail price of your car? (only for manufacturers)
- What are the maintenance costs for FCEV?
- How life expectancy of FCEV compares to BEV?
- What the maintenance of these vehicles entail and how much does it cost?
- What is the unique selling point of your FCEV compared to your BEV?
- What are the expected resale values of your BEV and FCEV after 3 years and 100,000 miles?

Fleet customers’ specific questions

- How many and what type of BEV and FCEV do you currently have in your fleet? (only for fleet consumers)
- What is the average annual range of such vehicles?
- Have you perceived a difference in performance? Any reliability issues?
- Has the battery of your BEV degraded to such extent that you have perceived a decrease on vehicle range?
- How do you typically procure electric vehicles?
- What is the typical mileage per year for BEV and FCEV, respectivel
- Do you have superchargers for your BEV?
- How do you finance the procurement of these vehicles? If via Contract Purchase, how much is the deposit, APR, length of the contract and balloon payment?
- Do you company has to pay any type of insurance premium for operating these vehicles?
- What is the schedule of cash outflows?

Appendix XII – NPV Methodology and Financing of Vehicles

Net Present cost and financing

The calculation of the TCO used in this research uses the Net Present Value (NPV) of all capital and operative expenditure (capex/opex). The NPV is considered as a suitable technique for financial decision making as it overcomes the flaws of the payback method, as reported by Burns and Walker (1997). The payback period does not i) consider the time value of money; ii) provide a monetary value that allows a clear comparison of what alternatives are preferable; and iii) consider returns beyond the payback period time horizon. The NPV allows the evaluation of specific rates of return and future cash flows at different points in time. The results presented in Chapter 5 show the lifecycle net present total costs of ownership (NPTCO) of a straight purchase made by a private user (as per *Equation 2*), and the NPTCO when the vehicles are procured by a commercial fleet via a contract purchase or with a contract hire. Under case 1 (straight purchase), the customer pays the vehicle cost upfront (in year 0) and it has no residual value. Customers should account for opportunity costs of investing their money in something, and for this reason, a cost of capital factor is applied. Similar principles apply to case 2, with the difference that as the contract last just 3 years, the fleet owner recovers a residual value when the car is sold. Fleet owners under case 3, lease (contract hire) their vehicles as this allows them better planning and it lowers risks by paying known and regular fixed monthly payments. In a leasing, the retail price and tax is paid by the lessor who charges regular payments to the lessee at a given interest rate. As no initial payment is made (C^0) by the buyer, the NPC is (typically) lower as NPV at period zero has higher impact than equivalent payments over longer time. As lessors have a strong bargaining power with automakers due to their large purchasing volumes, they can pass part of these savings to the lessees who might benefit from these discounts.

The regular forms of financing in the UK are presented in *Table 27*. A simplified example illustrating how different financing methods affect the NPC is shown in *Table 28*. This is relevant for BEV and FCEV automakers, as these vehicles are typically much more expensive than conventional cars and this can be taken in consideration when defining their strategies.

Equation 2 Net Present Cost formula.

$$\text{NPTCO} = \text{TCO}^0 + \sum_{t=1}^{n} \frac{TCO_t}{(1+r)^t}$$

Where

TCO^0=Initial investment (total costs of ownership when the vehicle is procured; period 0).
TCO_t=Cash flow payments in year t (total costs of ownership including capital and operating expenditures) at the end of the period t.
r = Rate of return, weighted average cost of capital.
n = Vehicle life expectancy (in years).
t = Period in year since the vehicle was procured.

When leasing cars, capital investment is deferred over time and the NPTCO tends to be lower than a straight purchase. The quotes of the leasing in *Table 26* are calculated applying a capital recovery factor (Equation *3*) over the length of the contract, and as all leasing, the residual value at the end of the agreement is zero.

Equation 3 Capital recovery factor.

$$A = C \times \frac{[(1+i)^n \times i]}{[(1+i)^n - 1]}$$

Where

A= Annual payment.

C= Capital investment.

i= Interest rate.

n= Life expectancy of the vehicle (in years).

Table *28* shows the importance of how much financial agreements can change the business case for procuring a car. The purchase of a £100k car with a 5% resale value at the end of its life, represents a total cash outflow of £95,000 over 5 years which equates to a net present cost of £96,895. If a company leases the same vehicle with the same retail price, the lessor could offer the vehicle to the lessee more cheaply. The reason for this, is that the lessee would end paying almost £15k more over the following 5 years, as there would not be an initial outlay payment (the expenditure would be spread over time). However, the total net present cost would decrease from £97k to £83k (net present savings of £14k).

Table 27. Some financial options for the procurement of vehicles.

Funding Options	Characteristics
Straight Purchase	The ownership of the electric vehicle belongs to the customer, who assumes all costs (including servicing, maintenance and tear and wear) and risks (reliability, fluctuations residual value). There is a big initial capital expense outlay (purchasing, insurance, servicing contracts, VAT, VED, etc.). Residual value is recovered at the moment that the vehicle is sold. NPC are higher than other funding alternatives because most expenses are incurrent at the moment of procuring the vehicles. Corporate buyers must reflect the purchase on the balance sheet as an asset.
Contract Hire (Operating leasing)	It is a long-term car rental with fixed costs. This is typically known as car-leasing. The customer pays a monthly fix rental fee for an agreed period of time that is the difference between retail value and residual value (depreciation, mileage, condition). At the end of the agreement, the customer (lessee) returns the car to the owner (lessor). Clauses include early termination penalties and annual mileage limits. Business can offset rental payments against taxable profit and claim 100% of VAT. The customer cannot include the asset in the balance sheet. VED is managed by the owner (lessor). Service and maintenance fees may be (or not) included in the contract.
Hire Purchase (HP)	It is a conditional sale (rent-to-own). The finance company owns the vehicle until the last payment is made. The customer pays a deposit that can reduce the monthly hiring payments. The loan is secured against the car (low risk). Full VAT is paid with initial deposit payment (reclaimable by the lessee). It appears on lessee’s balance sheet.
Contract Purchase (CP)	The same as HP but at the end of the agreement, the car can be bought, returned to the seller or used as equity (part-exchange) for a new vehicle (the future residual value of the vehicle is included in the original agreement – guarantee future value). If the vehicle ends being purchased or part-exchanged, then it is the same as a hire purchase. If the vehicle is not, it is similar to a contract hire.

Table 28. Comparison of the financial advantages of leasing an electric vehicle versus a cash buy for a £100,000 vehicle.

Purchase Agreement	RR	Years	Cash flows (£) Year							Buyer Pays	
			Initial Capital Investment		1	2	3	4	5 (RV)	Over 5 years	Net Present Cost (£)
Straight Purchase[30]	10.00%	5	100,000		0	0	0	0	5,000	95,000	96,895
Leasing Agreement	Interest Rate	Years	Cost Lessor	Cash flows (£) Year [Capital Recovery Factor]						Lessee Pays	
				0	1	2	3	4	5 (RV = 0)	Over 5 years	Net Present Cost (£)
Contract Hire	3.00%	5	100,000	0	21,835	21,835	21,835	21,835	21,835	109,177	82,774

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[30] Vehicle paid in cash

Appendix XIII – Total Cost of Ownership Calculation Methodology for a Private Car (Case 1)

Total Cost of Ownership

The TCO calculations use the NPC of relevant concepts. In the results, this is defined as net present total cost of ownership (NPTCO). The main assumptions for calculating the NPC and leasing rental payments and the TCO appear in Table *29*. The TCO excludes emission costs, as these are not currently internalised (beyond the VED). The savings from congestion charges and low emission zones access are not included because these depend on the location where customers live and how many times they access the areas where such schemes are implemented.

In average, UK cars drive 8,200 miles/year (DfT, 2016d), and last for 13.9 years. In the model, it is assumed that electric vehicles run the same as a diesel vehicle (11,200/year) adding up to 156,800 miles during their lifetime. However, it is likely that these vehicles may last much longer due to the lower tear and wear of their powertrain and drivetrain. This research considers two different types of customers. Large fleet operators lease their vehicles via contract hire which simplifies the financial management, as the lessor is responsible for all expenses or they procure the vehicles via a contract purchase agreement.

It has been assumed that private customers fund the purchase of their cars by themselves (despite that some of them may request personal loans or rely on private contract purchases). With a straight buy, as explained in Table *27*, the buyer is responsible for paying all the expenses (retail price, taxation, insurance, etc.). At the end, the buyer can sell the car to recover a residual value, or dispose of it (at a potential cost). Here it has been assumed that the residual value is zero after 14 years. Table *32* illustrates all capital and operative expenses and periods when these are experienced for a BEV. FCEV TCO is exemplified in

Period		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	Year		**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**202**
	Mileage	0	11,200	22,400	33,600	44,800	56,000	67,200	78,400	89,600	100,800	112,0
Capex	**Procurement (OTR)**	27,180										
	UK Subsidies	-4,500										
	Fast Charger + Installation	0										
	Residual value											
Opex	**VED**		0	0	0	0	0					
	Electricity Consumption		442	486	495	508	524	508	524	546	583	5

	Service Contract		168	168	168	168	168	168	168	168	168	1
	Tyres				286			286			286	
	Battery replacement										3,176	
	MOT				55	55	55	55	55	55	55	
	Insurance		455	455	455	455	455	455	455	455	455	4

Table *33*.

Table 29. Main assumptions used for the calculation of the TCO and NPV (Case 1)

NPV assumptions – Straight purchase private customer	
Cost of capital	8%
Lifetime vehicle	14 years [31]
TCO general assumptions:	
Retail prices	As reported by the manufacturers (includes VAT and delivery costs) for models sold in 2017.
UK subsidies	£4,500/car, at the moment of purchase.
Residual value	Zero (vehicle is disposed of at the end of its life).
Annual mileage	Total mileage over life of the vehicle 156,800. 11,200 miles/year.
VED	For cars over £40,000 VED is £310 for 5 years.
Service Contract	Averaged each year.
MOT	Starts in year 3 after purchase.
Tyres	Life 30,000 miles
Insurance costs	As quoted by Switch.com (May 2017). It is assumed that the insurance cost remain the same over the life of the vehicle.
Energy consumption	The one reported by the US DoE following the EPA driving cycle
Assumptions BEV	
Recharger	For private users, cost is £674 (most vehicles). Tesla £1,188 (including installation).
Electricity	Variable from 9.3 p/kWh for service fleets in 2017 to 17.9 p/kWh to residential customers in 2030, as per *Table 30*.
Battery replacement	Every 100,000 miles
Assumptions FCEV	
Hydrogen	From £6.2/kg in 2017 to £2/kg in 2030, as per Table *31*.
Ionic filter replacement	Every 50,000 miles

UK retail prices of all vehicles have been obtained directly from the manufacturers. Several models' prices were converted from foreign markets. Specifically, the Fiat e500 and the Honda Clarity FC from the USA and the Opel Ampera-e from Germany. The Smart Fortwo retail value was calculated by averaging three on-line journalistic sources. The annual insurance premiums for the vehicles not found in the UK market have been estimated at 1.6% of their retail value (this was the average for all premiums for BEV, excluding Tesla).

The vehicles with only a 240VAC/3.6 kW on board charger have been upgraded with a faster 7.2 kW on-wall unit. The costs of these were the ones supplied by vendors or the retail price of a Bosch PowerMax 2[32] (£674/unit). Commercial fleets may

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[31] SMMT (2016) states that the average age of a car at scrappage in 2016 was 13.9 years.

[32] Part number EL-51866-4018.

prefer to install a superfast recharging point capable of recharging a battery up to 80% typically under 1 hour. The cost of faster charging points appear in Table *19*.

Table 30. Retail prices electricity for different sectors from 2017 to 2030 (p/kWh at 2016 prices). Source: BEIS (2017b)

Year / Sector	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Residential	14.1	15.5	15.8	16.2	16.7	16.2	16.7
Services	9.3	10.5	10.9	11.4	12.0	11.7	12.1
Year / Sector	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Residential	17.4	18.6	18.8	18.3	19.2	18.6	17.9
Services	12.4	12.9	12.8	13.0	13.4	13.1	13.2

Table 31. Hydrogen costs (£/kg) delivered at the pump without taxes/excises. Adapted from: The Coalition (2010)

Year / Sector	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
H_2 cost (pump)	6.2	5.7	5.4	5.3	5.0	4.8	4.6
Year / Sector	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
H_2 cost (pump)	4.6	4.4	4.3	4.2	4.2	4.1	4.0

Subsidies in the UK for zero emissions cars are £4,500/vehicle. Zero emission cars are exempt from paying VED, except when their retail price is over £40,000 in which case, a VED of £310 must be paid the first 5 years of the life of the car. As a result, all FCEV must pay this expense while just the Tesla models have to do so among all the BEV. In these tables, the reader can perceive that these vehicles are exempt from paying MOT.

Electricity costs are based on the domestic retail price of electricity for private consumers and service company costs for fleet owners. BEIS (2017b) forecasts that electricity prices will be increasing in the long run. Hydrogen prices are assumed to be the same for all consumers and they will decrease over time due to economies of scale and scope from oil companies entering the market, as well as, new entrants from the renewable power industry, and efficiency improvements in the production methods. The forecast hydrogen costs appear in Table *31*. These costs are considerably higher than the targets expected by some organisations such as the US DoE, than aims at production costs much lower as illustrated in Table *7*.

Maintenance costs were obtained from vehicle manufacturers' websites or via personal communication with the automakers, according to the recommended service schedule and including parts and MOT. When this information was unable, maintenance costs were estimated at £0.015/mile. BEV assumed a battery replacement in year 8, as automakers guarantee those for 8 years or 100,000 miles, whichever sooner. Here it has been assumed that after 100,000 miles, the degradation of the battery is likely to affect vehicle range to such extent that a replacement is in order.

Insurance costs were obtained from uSwitch.com for a 42-year-old driver with 20 years of driving experience and 3 years no claim bonus, except for FCEV, as these were not found in the database. The insurance quote for the Toyota Mirai was obtained from the company website. Insurance for the other 2 models were extrapolated based on the relative cost compared to this vehicle. The same insurance premiums were assumed each year during the life of the vehicle.

Table 32. Components for the calculation of the TCO of a Volkswagen e-Golf bought by a private consumer and the periods when the costs are incurred (Case 1).

Period		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Year			**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Mileage		0	11,200	22,400	33,600	44,800	56,000	67,200	78,400	89,600	100,800	112,000	123,200	134,400	145,600	156,800
Capex	**Procurement (OTR)**	27,180														
	UK Subsidies	-4,500														
	Fast Charger + Installation	0														
	Residual value															0
Opex	**VED**		0	0	0	0	0									
	Electricity Consumption		442	486	495	508	524	508	524	546	583	590	574	602	583	561
	Service Contract		168	168	168	168	168	168	168	168	168	168	168	168	168	168
	Tyres				286			286			286		286			286
	Battery replacement										3,176					
	MOT				55	55	55	55	55	55	55	55	55	55	55	55
	Insurance		455	455	455	455	455	455	455	455	455	455	455	455	455	470

Table 33. Components for the calculation of the TCO of a Toyota Mirai bought by a private consumer and the periods when the costs are incurred (Case 1).

Period		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Year			**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Mileage		0	11,200	22,400	33,600	44,800	56,000	67,200	78,400	89,600	100,800	112,000	123,200	134,400	145,600	156,800
Capex	**Procurement (OTR)**	66,000														
	UK Subsidies	-4,500														
	Residual value															0
Opex	**VED**		310	310	310	310	310									
	Hydrogen Consumption		1,064	978	926	909	858	824	789	789	755	738	721	721	703	686
	Service Contract		168	168	168	168	168	168	168	168	168	168	168	168	168	168
	Tyres				286			286			286		286			286
	Ionic filter replacement						300				300					300
	MOT				55	55	55	55	55	55	55	55	55	55	55	55
	Insurance		1,054	1,054	1,054	1,054	1,054	1,054	1,054	1,054	1,054	1,054	1,054	1,054	1,054	1,054

Appendix XIV – Life Cycle Analysis Methodology

Lifecycle Analysis (LCA) of GHG emissions

The LCA analysis of the vehicles considered USA production facilities as the emission factors for energy inputs, energy balances and raw materials of these were unavailable in a European setting. However, the model used (GREET) allowed a higher degree of configuration of powertrains, vehicle weights, sizes of batteries and fuel cells than could be achieved by using different approaches such as LCA Simapro/Ecoinvent.

LCA is a technique used to evaluate the environmental impact of a product, process or activity through its entire lifecycle (Roy et al., 2009); from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (cradle-to-grave).Details regarding requirements and how to apply LCA are detailed in the ISO 14044 (ISO, 2006). In this study, LCA aggregates two different tools. While vehicle manufacturing emissions have been calculated using ‘Greenhouse gases, Regulated Emissions, and Energy use in Transportation’ (GREET) 2016 R1 (ANL, 2017). GREET allows the evaluation of several alternative powertrain vehicle technologies on a vehicle-cycle basis (see Table *34*), considering the consumption of total resources (raw materials), energy, and water and it calculates GHG (CO_2, CH_4, N_20) and air quality emissions (VOC, CO, NO_X, PM_{10}, $PM_{2.5}$, BC, SO_X). The model allows a high degree of customisation for configuring different types of vehicles, including BEV and FCEV. Some of the assumptions made by GREET in regards to vehicle components and materials composition appear in Table *35* and Table 36.

Table 34. Vehicle systems included in Greet 2016 R1. Adapted from: ANL (2006)

System	BEV	FCEV
Body system	x	x
Powertrain system	x	x
Chassis system	x	x
Transmission system	x	x
Traction motor	x	x
Generator	x	
Electronic controller	x	x
Fuel cell auxiliary system		x
Batteries	x	x
Fluids (excluding fuel)	x	x

Table 35. Vehicle Components Composition (% by wt). Source: ANL (2017)

Vehicle Subsystem	EV: Conventional Material	FCV: Conventional Material
Powertrain System (including BOP)	4.79%	7.23%
Transmission System	5.73%	2.81%
Chassis (w/o battery)	28.90%	25.00%
Traction Motor	7.18%	4.22%
Generator	0.00%	0.00%
Electronic Controller	5.90%	3.68%
Fuel Cell On-board Storage	0.00%	7.72%
Body: including BIW, interior, exterior, and glass	47.50%	49.35%

Table 36. Vehicle Material Composition (% by wt): aggregated by each component. Source: ANL (2017).

Vehicle Material Composition	**ICEV: Conventional Material**	**EV: Conventional Material**	**FCV: Conventional Material**
Steel	62.9499%	65.4950%	60.1952%
Stainless Steel	0.0000%	0.0000%	2.8889%
Cast Iron	10.2900%	1.9941%	1.7303%
Wrought Aluminum	1.8990%	1.4784%	2.1218%
Cast Aluminum	4.4631%	5.6485%	3.4990%
Copper/Brass	1.8799%	5.7950%	3.3691%
Magnesium	0.0185%	0.0190%	0.0197%
Glass	2.9994%	3.0872%	3.2077%
Average Plastic	11.3423%	11.9467%	12.0652%
Rubber	2.1873%	1.7274%	1.9497%
Carbon Fiber-Reinforced Plastic for High Pressure Vessels	0.0000%	0.0000%	5.0634%
Glass Fiber-Reinforced Plastic	0.0000%	0.0000%	0.5329%
Nickel	0.0000%	0.0000%	0.0001%
PFSA	0.0000%	0.0000%	0.0448%
Carbon Paper	0.0000%	0.0000%	0.1547%
PTFE	0.0000%	0.0000%	0.1854%
Platinum	0.0005%	0.0000%	0.0013%
Silicon	0.0000%	0.0000%	0.0790%
Carbon	0.0000%	0.0000%	0.0197%
Others	1.9702%	2.8087%	2.8722%

Fuel-cycle analysis is also possible with GREET, but as pathways located in the USA differ considerably from the UK ones, energy WTT emissions have been calculated with UK emission factors plus the embedded. Well-to-tank emissions from electricity were calculated according to the GHG emissions factors reported by CCC (2015) in Table *37*. Based on the energy consumption of each vehicle in kWh/100km, total carbon emissions have been calculated multiplying this by the carbon intensity of the grid each year and the total mileage during the life of the vehicle. WTT emissions of hydrogen have been calculated assuming that it is produced via SMR. The carbon intensity of the natural gas grid is 209 gCO_2e/kWh over the whole period and the efficiency of the production process is 79%. This results in 295 gCO2/kWh, including the embedded emissions of the production infrastructure (1.2 gCO_2e/kWh). The latter was calculated with SIMAPRO and the EcoInvent database. The water footprint is 0.27L/kg H2 and pumping this water has an almost negligible carbon footprint of 0.095 gCO_2e/kWh. The emission factor is multiplied by hydrogen consumption in kWh/100 mi for each FCEV. This approach could be inappropriate if a Green Hydrogen Standard were developed and guarantees of origin contracts were used to the supply of hydrogen. It that were the case, it is likely that carbon emissions would decrease to 10 gCO_2e/kWh or under, as proposed by Certifhy (2016). Similarly, the deployment of Carbon Capture and Sequestration (CCS) technologies could decrease emissions to around 29 gCO_2e/kWh.

Table 37. Emission factors electricity (gCO_2e/kWh). Adapted from: CCC (2015); National Grid (2016).

Year	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Carbon intensity UK generated electricity	459	378	146	38	11	2	1	1

Appendix XV – Costs of the Components of the Total Cost of Ownership for a Private Car Straight Purchase

Table 38 and *Table 39* include the results of the market research for BEV and FCEV costs. These are the baseline figures used to calculate the total cost of ownership of each vehicle.

Here is relevant to highlight that the price of the battery packs are not proportional between all the vehicles of the sample. Current 2017 prices for Tesla are estimated at $190/kWh, prices for Chevrolet is $150/kWh and for the rest of vehicles $220/kWh. The literature indicated that by 2020, those prices will be half. This seems too optimistic but the model assumes that this will be the cost by 2026, the moment when the batteries will need to be replaced.

Table 38. Prices of the different components of the TCO for the BEV commercialised in May 2017. The values in the grey cells have been extrapolated from similar vehicle models. Battery cost replacement assume price in 8 years' time.

Brand	Model	Retail Price	Recharger Upgrade	UK Subsidies	VED	Insurance	Maintenance	Battery Replacement	Tyres
BMW	i3 BEV/60 (A)	31,440	0	-4,500	0	470	168	1,952	286
BMW	i3 BEV/94 (A) without	32,330	0	-4,500	0	510	168	2,927	286
Chevrolet	Bolt / Ampera-e	31,464	0	-4,500	0	502	168	3,629	286
Fiat	500e	25,645	674	-4,500	0	410	168	2,129	152
Ford	Focus Electric Hatch	31,395	0	-4,500	0	505	168	2,972	286
Hyundai	IONIQ Electric	28,995	674	-4,500	0	504	168	2,484	286
Kia	Soul EV	29,995	674	-4,500	0	480	168	2,395	286
Mercedes	B250e	34,580	674	-4,500	0	575	168	2,484	234
Mitsubishi	i-MIEV ES	18,544	674	-4,500	0	359	168	1,419	286
Nissan	LEAF S Acenta	30,290	674	-4,500	0	629	132	2,661	286
Smart	ForTwo Electric Drive	23,273	674	-4,500	0	372	168	1,561	152
Volkswagen	e-Golf SE	27,180	0	-4,500	0	455	168	3,176	286
Tesla	Model S 75D	61,880	750	-4,500	310	849	983	5,746	333
Tesla	Model X AWD 75D	75,400	750	-4,500	310	920	983	5,746	333

Table 39. Prices of the different components of the TOC for the FCEV commercialised in 2017. The values in the grey cells have been extrapolated from different models or foreign markets. (N/A=Not applicable). All prices are in GBP (2017).

Brand	Model	Retail Price	Recharger Upgrade	UK Subsidies	VED	Insurance	Maintenance	Battery Ionic Filter	Tyres
Honda	Clarity Fuel Cell	67,849	N/A	-4,500	310	1,086	168	300	286
Hyundai	Tucson FC / ix35	57,605	N/A	-4,500	310	922	168	300	286
Toyota	Mirai	66,000	N/A	-4,500	310	1,054	168	300	286

Appendix XVI – Costs of the Components of the Total Cost of Ownership for a Car Fleet Bought Via Contract Purchase (Case 2)

From an operational point of view, with the right refuelling infrastructure in place, FCEV work very similarly to how conventional cars do. BEV, however, present the challenge of the recharging time. A world leader rental company communicated that they operate BEV and FCEV in two differentiated types of services. BEV typically operate in car-sharing/car club context and run 12,000 miles/year. FCEV are used in a private hire context driving for 33,000-36,000 miles/year[33]. BEV need to be recharged once a day which could be inconvenient if a customer needs the vehicle immediately. This also makes very difficult to achieve the high mileage that FCEV can offer. As these cars have to be cleaned each time they are offered to a different customer, it can be argued that recharging time might not be so critical, as a battery can be topped-up 80% in around 1 hour. Nevertheless, these superchargers tend to be very expensive. FCEV offer fewer risks for commercial fleets, resulting in better operational performance than BEV. Higher utilisation ratios can improve the business case for FCEV when long mileage can be serviced.

In *the* example, it has been assumed that corporate buyers can get a 10% discount on all retail prices (purchasing, chargers, maintenance) due to their large purchasing volume which gives them a high negotiating bargaining power.

Table *41* shows the expenses and the periods in which these are incurred for a commercial fleet of BEV and

Period		**0**	**1**	**2**	**3**
Year			**2017**	**2018**	**2019**
Mileage		0	32,000	64,000	96,000
Capex	**Deposit (30%)**	7,339			
	Monthly Payments		3,728	3,728	3,728
	Option to Purchase fee	10			
	UK Subsidies	-4,500			
	Fast Charger + Installation	0			
	Option Final Payment				7,339
	Resale value				-3,293

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[33] From an economic perspective, the difference with the case exposed in this Section and the fleet company mentioned here is that the company does not pay insurance premiums as the vehicles are all self-insured by the end user. However, it was chosen to include insurance costs to reflect the cost for a company using cars driven autonomously.

Opex	**VED**		0	0	0
	Electricity				
	Service Contract		151	151	151
	Tyres		257	257	257
	Battery replacement				
	MOT				55

Table *42* shows the ones for a fleet of FCEV. Commercial fleets' cars mileage is likely to be much higher than private cars. Here, it has been assumed that vehicles do around 32,000 miles/ year and after 3 years they are sold into the market. The residual value of FCEV is difficult to calculate, as there are not second hand cars available in the UK market. However, after checking some statistics from CAP and the respondents of the case studies, it is believed that FCEV could maintain 47% of the retail value and BEV around 13% (after 96,000 miles / 3 years). The reason for this difference is double. Firstly, because the resale value has some relationship to the retail value of the car when it is bought, and FCEV and much more expensive than BEV. The second reason is that battery packs are guaranteed for 100,000 miles, and in this case when BEV are sold, the guarantee of their batteries is almost expired. Unless the new buyer replaces it, battery degradation will most likely decrease vehicle range noticeably. To put this in perspective, a Toyota Prius hybrid could retain 37% of its value under the same conditions. As FCEV do not suffer significant degradation after 3 years of use (typically fuel cells last at least 5,000 hours), the residual value is likely to be much higher than BEV.

Table 40. Main assumptions used for the calculation of the TCO and NPV commercial vehicles funded via contract purchase (Case 2).

NPV assumptions	
Cost of capital	8%
Capital recovery factor method – Hire Purchase commercial fleet.	
Interest rate (APR)	3%
Lifetime Contract	3 years
TCO general assumptions:	
Retail prices	As reported by the manufacturers (includes VAT and delivery costs) for models sold in 2017 minus 10% discount.
UK subsidies	£4,500/car, at the moment of purchase
Residual value	13.47% for BEV and 47% for FCEV
Annual mileage	Total mileage over life of the vehicle 96,000 (32,000 miles/year)
VED	For cars over £40,000 VED is £310 for 5 years

MOT	Starts in year 3.
Tyres	Life 30,000 miles
Insurance costs	None. All vehicles are self-insured
Energy consumption	The one reported by the US DoE following the EPA driving cycle
Assumptions BEV	
Recharger	For most vehicles £674 and £750 for Tesla models (including installation), -10% discount.
Electricity	None. Paid by the driver.
Battery replacement	None (vehicles do not exceed 100,000 miles)
Assumptions FCEV	
Hydrogen	None. Paid by the driver
Ionic filter replacement	Every 50,000 miles

In the example, contract purchases from the fleet operators require a 30% deposit, the payment of a £10 option fee to purchase the vehicle at the end of the contract, and an optional payment of 5% to purchase the vehicle. The monthly quotas are the result of the credit balance (retail price minus deposit) payable over the period of the contract at a 3% APR. However, VAT and monthly payments can be claimed back against taxable profits. When tax is claimed the capital costs at the moment of the buy is inferior to the sum of the VAT (claimed back) and the UK subsidy (£4,500).

In the example, it has been assumed that corporate buyers can get a 10% discount on all retail prices (purchasing, chargers, maintenance) due to their large purchasing volume which gives them a high negotiating bargaining power.

Table 41. Components for the calculation of the TCO of a leased Volkswagen e-Golf bought by a fleet owner and the periods where the costs are incurred.

Period		**0**	**1**	**2**	**3**
Year			**2017**	**2018**	**2019**
Mileage		0	32,000	64,000	96,000
Capex	**Deposit (30%)**	7,339			
	Monthly Payments		3,728	3,728	3,728
	Option to Purchase fee	10			
	UK Subsidies	-4,500			
	Fast Charger + Installation	0			
	Option Final Payment				7,339
	Resale value				-3,293
Opex	**VED**		0	0	0
	Electricity				
	Service Contract		151	151	151
	Tyres		257	257	257
	Battery replacement				

	MOT				55

Table 42. Components for the calculation of the TCO of a leased Toyota Mirai bought by a fleet owner and the periods where the costs are incurred.

Period		0	1	2	3
Year			2017	2018	2019
Mileage		0	32,000	64,000	96,000
Capex	**Deposit (30%)**	17,820			
	Monthly Payments		9,053	9,053	9,053
	Option to Purchase fee	10			
	UK Subsidies	-4,500			
	Option Final Payment				17,820
	Resale value				-27,918
Opex	**VED**		310	310	310
	Hydrogen				
	Service Contract		151	151	151
	Tyres		257	257	257
	Ionic filter replacement			270	
	MOT				55

Table 43. Prices (£) of the different components of the TOC for the BEV commercialised in 2017. Deposit and optional final payment 30%.

Brand	Model	B2B Price	Deposit	Total Credit	Monthly Pay	Optional Final Payment	Option to purchase	VAT	UK Subsidy	Recharger Upgrade	VED	Maintenance	Tyres	Resale Value
BMW	i3 BEV/60	28,296	8,489	19,807	-359	-8,489	10	-5,659	-4,500	0	0	151	257	-3,809
BMW	i3 BEV/94	29,097	8,729	20,368	-370	-8,729	10	-5,819	-4,500	0	0	151	257	-3,916
Chevrolet	Bolt	28,318	8,495	19,822	-360	-8,495	10	-5,664	-4,500	0	0	151	257	-3,812
Fiat	500e	23,081	6,924	16,156	-293	-6,924	10	-4,616	-4,500	607	0	151	137	-3,107
Ford	Focus Electric	28,256	8,477	19,779	-359	-8,477	10	-5,651	-4,500	0	0	151	257	-3,803
Hyundai	IONIQ Electric	26,096	7,829	18,267	-331	-7,829	10	-5,219	-4,500	607	0	151	257	-3,512
Kia	Soul EV	26,996	8,099	18,897	-343	-8,099	10	-5,399	-4,500	607	0	151	257	-3,634
Mercedes	B250e	31,122	9,337	21,785	-395	-9,337	10	-6,224	-4,500	607	0	151	211	-4,189
Mitsubishi	i-MIEV ES	16,690	5,007	11,683	-212	-5,007	10	-3,338	-4,500	607	0	151	257	-2,246
Nissan	LEAF S Acenta	27,261	8,178	19,083	-346	-8,178	10	-5,452	-4,500	607	0	119	257	-3,669
Smart	ForTwo Electric	20,946	6,284	14,662	-266	-6,284	10	-4,189	-4,500	607	0	151	137	-2,819
Volkswagen	e-Golf SE	24,462	7,339	17,123	-311	-7,339	10	-4,892	-4,500	0	0	151	257	-3,293
Tesla	Model S 75	55,692	16,708	38,984	-707	-16,708	10	-11,138	-4,500	675	310	1,050	300	-7,496
Tesla	Model X AWD 75D	67,860	20,358	47,502	-862	-20,358	10	-13,572	-4,500	675	310	1,200	300	-9,134

Table 44. Prices of the different components of the TOC for the FCEV commercialised in 2017. The values in the grey cells have been extrapolated from different models or foreign markets. (N/A=Not applicable). All prices are in GBP (2017).

Brand	Model	B2B Price	Deposit	Total Credit	Monthly Payments	Optional Final Payment	Option to purchase	VAT	UK Subsidy	Ionic Filter	VED	Maintenance	Tyres	Resale Value
Honda	Clarity FC	61,064	18,319	42,745	-776	-18,319	10	-12,213	-4,500	270	310	151	257	-28,700
Hyundai	ix35	51,845	15,553	36,291	-658	-15,553	10	-10,369	-4,500	270	310	151	257	-24,367
Toyota	Mirai	59,400	17,820	41,580	-754	-17,820	10	-11,880	-4,500	270	310	151	257	-27,918

Appendix XVII – Example of the NPTCO of a BEV and a FCEV (Case 2)

Table 45. NPTCO of a BMW i3/60.

Period		**0**	**1**	**2**	**3**
Year			**2017**	**2018**	**2019**
Mileage		0	32,000	64,000	96,000
Capex	**Deposit (30%)**	8,489			
	Monthly Payments		4,312	4,312	4,312
	Option to Purchase fee	10			
	UK Subsidies	-4,500			
	Fast Charger + Installation	0			
	Option Final Payment				8,489
	Resale value				-3,809
Opex	**VED**		0	0	0
	Electricity				
	Service Contract		151	151	151
	Tyres		257	257	257
	Battery replacement				
	MOT				55
		3,999	4,721	4,721	9,456
NPTCO	19,924				

Table 46. NPTCO of a Tesla 75D.

Period		**0**	**1**	**2**	**3**
Year			**2017**	**2018**	**2019**
Mileage		0	32,000	64,000	96,000
Capex	**Deposit (30%)**	16,708			
	Monthly Payments		8,488	8,488	8,488
	Option to Purchase fee	10			
	UK Subsidies	-4,500			
	Fast Charger + Installation	675			
	Option Final Payment				16,708
	Resale value				-7,496
Opex	**VED**		310	310	310
	Electricity				
	Service Contract		1,050	1,050	1,050
	Tyres		300	300	300
	Battery replacement				
	MOT				55
		12,893	10,147	10,147	19,414
NPTCO	46,399				

Table 47. NPTCO of a Toyota Mirai

Period		0	1	2	3
Year			2017	2018	2019
Mileage		0	32,000	64,000	96,000
Capex	Deposit (30%)	17,820			
	Monthly Payments		9,053	9,053	9,053
	Option to Purchase fee	10			
	UK Subsidies	-4,500			
	Option Final Payment				17,820
	Resale value				-27,918
Opex	VED		310	310	310
	Hydrogen				
	Service Contract		151	151	151
	Tyres		257	257	257
	Battery replacement			270	
	MOT				55

NPTCO 30,770

Companies can claim 100% of the cost of the vehicles via First Year Allowances.

Appendix XVIII – Example of the NPTCO of a BEV and A FCEV (Case 3)

The monthly payments of the leasing are the result of the credit given to the corporate buyer. This credit is calculated by subtracting to the retail price the residual value of the vehicle (at the end of the contract), plus an initial payment of three times the regular monthly payments and the subsidy from the Government. The remaining credit is funded for 47 months at an APR of 3%. This allows the lessee to manage cash flows more easily as all monthly rentals are the same. At the end of the contract, the vehicle is returned. The costs of each element considered in the calculation of the NPTCO for BEV and FCEV appear in Table *49* and Table *50*. Specific details of the calculation of one of the BEV appears in Table *51*. Compared to a contract purchase, leasing is more expensive; however, it presents the advantage of transferring the depreciation risks to the lessor and it allows the lessee to have a clear idea of how much revenue needs to generate from each vehicle per month to make a profit. Furthermore, as it is not included in the balance sheet as an asset, in some cases it can improve some financial ratios.

The depreciation ratios have been estimated to be the same as case 2, because despite than cars are 1 year older, the battery pack of the BEV is replaced at 100,000 miles, and when the vehicle is returned to the lessor, it still has 60,000 miles or 7 years of guarantee, whichever is sooner. FCEV residual value has been reduced by 48% compared to case 2, as the vehicle has 48% more mileage and is one year older.

Table 48. Assumptions calculations NPTCO operating lease commercial fleet.

NPV assumptions	
Cost of capital	8%
Capital recovery factor method – Hire Purchase commercial fleet.	
Interest rate (APR)	3%
Lifetime Contract	4 years
TCO general assumptions:	
Procurement	Contract Hire (Operating Lease)
UK subsidies	£4,500/car, at the moment of purchase. The lessor uses this subsidy to reduce the credit base.
Residual value	13.47% for BEV and 21.5% for FCEV. The lessor uses this subsidy to reduce the credit base.
Annual mileage	Total mileage over life of the vehicle 140,000 (35,000 miles/year.
VED	For cars over £40,000 VED is £310 for 5 years
MOT	Paid in years 3 and 4.
Maintenance costs	Paid by the lessee.
Tyres	Life 30,000 miles
Insurance costs	N/A. Vehicles are self-insured
Energy consumption	The one reported by the US DoE following the EPA driving cycle
Assumptions BEV	
Recharger	For most vehicles £674 and £750 for Tesla models (including installation), -10% discount.
Electricity costs	None. Paid by the driver
Battery replacement	1 replacement every 100,000 miles
Assumptions FCEV	
Hydrogen costs	None. Paid by the driver
Ionic filter replacement	Every 50,000 miles. The lessee pays all maintenance costs.

Table 49. Prices of the different components of the NPTCO for BEV commercialised in May 2017 under a leasing contract.

Brand	Model	B2B Price	Deposit (3X)	Total Credit	Monthly Payments	UK Subsidies	Recharger Upgrade	VED	Maintenance	Battery Replacement	MOT Y3/4	Tyres	Resale Value
BMW	i3 BEV/60	28,296	1,268	18,720	423	4,500	0	0	151	1,952	55	257	3,809
BMW	i3 BEV/94	29,097	1,312	19,368	437	4,500	0	0	151	2,927	55	257	3,916
Chevrolet	Bolt	28,318	1,269	18,737	423	4,500	0	0	151	3,629	55	257	3,812
Fiat	500e	23,081	982	14,492	327	4,500	607	0	151	2,129	55	137	3,107
Ford	Focus Electric	28,256	1,266	18,686	422	4,500	0	0	151	2,972	55	257	3,803
Hyundai	IONIQ Electric	26,096	1,147	16,936	382	4,500	607	0	151	2,484	55	257	3,512
Kia	Soul EV	26,996	1,197	17,665	399	4,500	607	0	151	2,395	55	257	3,634
Mercedes	B250e	31,122	1,423	21,010	474	4,500	607	0	151	2,484	55	211	4,189
Mitsubishi	i-MIEV ES	16,690	631	9,312	210	4,500	607	0	151	1,419	55	257	2,246
Nissan	LEAF S Acenta	27,261	1,211	17,881	404	4,500	607	0	119	2,661	55	257	3,669
Smart	ForTwo Electric	20,946	865	12,761	288	4,500	607	0	151	1,561	55	137	2,819
Volkswagen	e-Golf SE	24,462	1,058	15,611	352	4,500	0	0	151	3,176	55	257	3,293
Tesla	Model S 75	55,692	2,772	40,924	924	4,500	675	310	1,050	5,746	55	300	7,496
Tesla	Model X AWD 75D	67,860	3,440	50,786	1,147	4,500	675	310	1,200	5,746	55	300	9,134

Table 50. Prices of the different components of the NPTCO for FCEV commercialised in May 2017 under a leasing contract.

Brand	Model	B2B Price	Deposit (3X)	Total Credit	Monthly Payments	UK Subsidies	VED	Maintenance	Ion Filter Replacement	MOT Y3/4	Tyres	Resale Value
Honda	Clarity Fuel Cell	61,064	2,755	40,655	918	4,500	310	151	270	55	257	13,154
Hyundai	Tucson FC / ix35	51,845	2,295	33,881	765	4,500	310	151	270	55	257	11,168
Toyota	Mirai	59,400	2,671	39,433	890	4,500	310	151	270	55	257	12,796

Table 51. Elements and schedule of the payments for the calculation of the NPTCO of a Tesla Model X 75D (left) and Toyota Mirai (right) (Case 3).

Period		0	1	2	3	4
Year			2017	2018	2019	2020
Mileage		0	35,000	70,000	105,000	140,000
Opex	Deposit (3X)	3,440				
	Monthly Payments		13,760	13,760	13,760	13,760
	Fast Charger + Installation	675				
	VED		310	310	310	310
	Service Contract		1,200	1,200	1,200	1,200
	Tyres		300	300	300	300
	Battery replacement				5,746	
	MOT				55	55
		4,115	15,569	15,569	21,370	15,624
NPTCO	60,327					

Period		0	1	2	3	4
Year			2017	2018	2019	2020
Mileage		0	35,000	70,000	105,000	140,000
Opex	Deposit (3X)	17,820				
	Monthly Payments		10,684	10,684	10,684	10,684
	VED		310	310	310	310
	Service Contract		151	151	151	151
	Tyres		257	257	257	257
	Ionic filter replacement			270	270	
	MOT				55	55
		17,820	11,402	11,672	11,727	11,457
NPTCO	56,116					

Appendix XIX – The Kano Model for Innovation Applied To Electric Vehicles

Currently most electric vehicles offer high torque (power) and fast acceleration, and are very quiet. This may be unexpected and cause delight among consumers. However, after a while, these features become standard attributes and excitement becomes a basic feature, eliminating any competitive advantage. To keep customers engaged with the brand, automakers will have to deliver further innovations. Unless new battery chemistries are developed (e.g. Lithium air) FCEV will enjoy a unique selling point within the zero emissions vehicle market. The linear needs of consumers include better fuel economy (hence range) and faster recharging times in the case of BEV. Satisfaction increases with improved performance. Basic 'needs' such as the safety of FCEV and reliability are not always expressed, as everybody assumes that they are a given; however, they can cause dissatisfaction if they are not present (all these concepts are illustrated in *Figure 33*). This model infers the need for gaining customer insight to understand the attributes that they value especially and avoiding later disappointment, as customers do not tend to express the basic or exciting qualities of products.

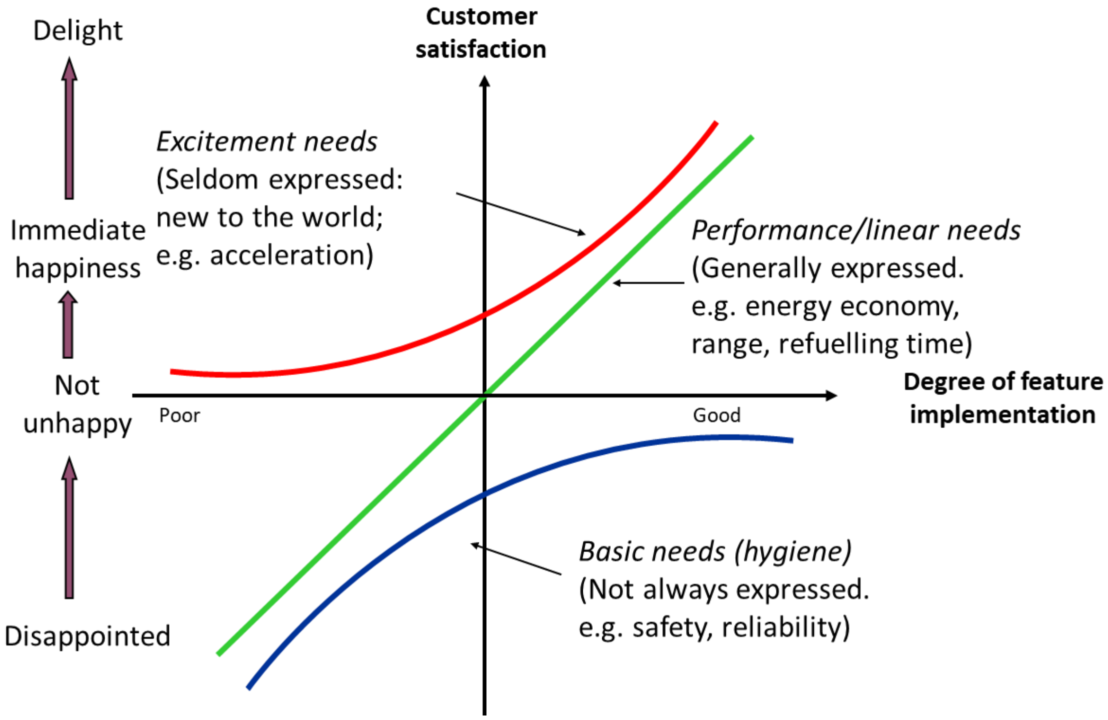

Figure 33. Kano model applied to electric vehicles. Adapted from Kano et al. (1984)

Appendix XX – Statistics travelling patterns GB drivers

The Tables below indicate the average trip distance driven by cars since 2005 and the number of trips that each individual drives according to the distance driven. This has been used to jusfify that BEV have enough range for most trips.

Table 52. Table NTS0308. Average number of trips by trip length and main mode: Great Britain, 2012. Adapted from: DfT (2016c)

	Trips per person per year							
Main mode	**Under 1 mile**	**1 to under 2 miles**	**2 to under 5 miles**	**5 to under 10 miles**	**10 to under 25 miles**	**25 to under 50 miles**	**50 to under 100 miles**	**100 miles and over**
Private:								
Car / van driver	24	64	134	89	65	17	6	3
Cumulative %	6.0%	22.0%	55.3%	77.5%	93.7%	97.9%	99.4%	100.0%
All modes	190	174	264	163	114	31	12	6
Cumulative %	19.9%	38.1%	65.8%	82.8%	94.8%	98.1%	99.3%	100.0%

Table 53. Table NTS 0306. Average trip length by main mode: Great Britain. Adapted from: DfT (2016a)

Miles/number/thousands

Main mode	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Private:								
Car / van driver	8.4	8.5	8.9	8.5	8.4	8.4	8.6	8.4
All modes	6.9	6.9	7.3	7.0	7.0	7.0	7.1	7.0