Chapter 6
Environmental impact of hybrid and electric vehicles

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Abstract

Hybrid and electric vehicles play a critical role in reducing global greenhouse gas emissions, with transport estimated to contribute to 14% of the 49 gigatonnesCO_2eq produced annually. Analysis of only the conversion efficiency of powertrain technologies can be misleading with pure battery electric and hybrid vehicles reporting average efficiencies of 92% and 35% in comparison with 21% for internal combustion engine vehicles. A fairer comparison would be to consider the well-to-wheel efficiency which reduces the numbers to 21-67%, 25% and 12% respectively. The large variation in well-to-wheel efficiency of pure battery electric vehicles highlights the importance of renewable generation to achieve true environmental benefits. When calculating the energy return on investment of the various technologies based on the current energy generation mix, hybrid vehicles show the greatest environmental benefits, though this would change if electricity was made with high amounts of renewables. In an extreme scenario with heavy coal generation, the CO_2eq return on investment can actually be negative for pure electric vehicles, highlighting the importance of renewable generation further. The energy impact of production is generally small (~6% of lifetime energy) and similarly recycling is of a similar magnitude, however is less well studied.

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1. Introduction

In order to achieve reductions in greenhouse gas (GHG) emission from the transport sector, hybrid and electric vehicle (EV) technology will be essential [1–3]. The Intergovernmental Panel on Climate Change estimated that in 2010, 49 gigatonnesCO_2eq was produced globally and of this, 14% was attributed to transport [4]. The International Energy Agency (IEA) highlighted the importance of reducing GHG emissions in 2009 by stating that if current trends were to continue, transport related CO_2 emissions would increase by 80% in 2050 making it extremely difficult to maintain atmospheric concentrations below a target of 450 ppm [5]. As of 2015, 1.3 million EVs were in use globally, which represents a compound average growth rate (CAGR) of 67% since 2012 [6]. Yet, despite this rapid growth, EV sales are still only a small proportion of the 90 million automobiles which are produced annually [7], though this is expected to shift in the coming years and will have regional differences. Future EV volumes vary from source to source, and there is no definitive forecast but indicative targets from the IEA suggests that if 140 million EVs are deployed by 2030 there would be a 50% chance of limiting average global temperature increases to 2°C [8].

In 2010, the European-wide fleet averaged emissions from passenger vehicles were approximately 160 gCO_2/km. Through a combination of engine downsizing and vehicle lightweighting, it is predicted that the approximate lower limit for a fossil fuel diesel internal combustion engine (ICE) is 85 gCO_2/km. Through hybridisation of the diesel ICE with energy storage technologies, this is envisaged to decrease to approximately 60 gCO_2/km, however carbon reductions beyond this towards longer term targets of 20 gCO_2/km can only be achieved with pure battery electric vehicles (BEV) [9]. However, it is important to understand that EV introduction is only part of the solution to reducing transport based GHG emissions and other factors such as renewable generation also need to be considered.

To analyse the potential environmental impact of EVs it is important to understand the variations in technology types and their characteristics. EVs as a whole can broadly be divided into 3 main categories: hydrogen fuel cell vehicles (FCV), pure BEVs and hybrid electric vehicles (HEV), with HEVs having further subdivisions based on the degree of hybridisation and powertrain configuration. FCVs, which are close to commercialisation, convert hydrogen into electrical energy through a proton exchange membrane fuel cell (PEMFC) with the only by-product being water. Full BEVs only use electrical energy provided from a battery and have the advantage of being zero-emission at the point of use, however still suffer from problems such as limited range, long charging times and higher capital cost compared to ICE powered vehicles. HEVs, which combine an energy storage element to an ICE, whilst not fully zero-emission do offer improvements in fuel economy. This is achieved through engine downsizing, reduced ICE transient loads and operation at a more efficient point by means of load shifting via the energy storage device. The absolute efficiency gains varies depending on the powertrain design and applied drive cycle [10].

A high level comparison by Pollet et al. [11] of the various vehicle technologies currently/close to commercialisation is presented in Table 1 to highlight some of the key metrics characteristic of different vehicle powertrains.

Table 1: Comparison of petrol, hybrid and electrical storage systems in four leading vehicles [11]

	Conventional	**Hybrid**	**Hydrogen**	**Battery**
Reference vehicle	Volkswagen Golf VI	Toyota Prius III	Honda FCX Clarity	Nissan Leaf
Fuel weight (kg)	40.8	33.3	4.1	171
Storage capacity (kWh)	500	409	137	24

Specific energy (Wh primary/kg fuel)	12,264	12,264	33,320	140
Storage system weight (kg)	48	40	93	300
Specific energy (Wh primary/kg of storage)	10,408	10,261	1,469	80
Net power (kW)	90	100	100	80
Power plant and auxiliary weight (kg)	233	253	222	100
Specific energy (Wh primary/kg total equipment)	1,782	1,398	315	60
Average conversion efficiency (%)	21	35	60	92
Effective storage capacity (kWh useable)	105.0	143.1	82.0	22.1
Specific energy (Wh usable/kg total equipment)	374	486	260	55

From Table 1, the most evident contrast between conventional ICE vehicles and BEVs is the difference in the specific energy. If only considering the specific energy (Wh primary/kg fuel) then there is nearly 2 orders of magnitude difference between the technologies. However, only considering these raw metrics is unfair as the conversion efficiency of a battery can be up to 4 times greater than an ICE. The specific energy (Wh usable/kg total equipment) is therefore a more suitable comparison metric. Whilst BEVs are still lower than ICE's, the difference is less than 1 order of magnitude, which can potentially be surmounted with innovations in battery chemistries and pack engineering. Focusing on the specific energy (Wh usable/kg total equipment), FCVs are already competitive and hybrid electric vehicles (HEV) are superior, however the key challenges here include cost, lifetime and refuelling infrastructure.

The analysis shown in Table 1, which includes the average conversion efficiency, whilst useful can also be misleading from an overall efficiency perspective. Table 2 shows the well-to-wheel (WtW) efficiency of the various powertrain technologies which is more useful to consider from an environmental perspective. The large variation in the WtW efficiency of BEVs is mainly due to the range in well-to-tank efficiency (WtT) and highlights the importance of considering how the electricity for BEVs is generated.

Table 2: Typical well-to-tank, tank-to-wheel and well-to-wheel efficiencies of each technology [11]

Vehicle type	Well to tank	Tank to wheel					Well to wheel
BEV	32-100%	Charger 90%	Battery 92%	Inverter 96%	Motor 91%	Mechanical 92%	21.3-66.5%
H2 FCEV	75-100%	Fuel cell 51.8%		Inverter 96%	Motor 91%	Mechanical 92%	31.2-41.6%
Hybrid	82.2%			30.2%			24.8%

Diesel	88.6%			17.8%			15.8%
Petrol	82.2%			15.1%			12.4%

Acknowledging the efficiency benefits of BEVs, one of the key barriers to their mainstream adoption is cost. From a historical perspective, the economies of scale and learning curves play a large part in the price of the batteries which has shown a significant decrease in recent years with an estimated industry average cost of approximately 1,300 $/kWh in 2006 falling to 400 $/kWh in 2014 as shown in Figure 1. Whilst the cost reductions have been significant, it is generally understood that in order to be cost competitive with ICEs the cost of the battery has to fall to approximately 150 $/kWh.

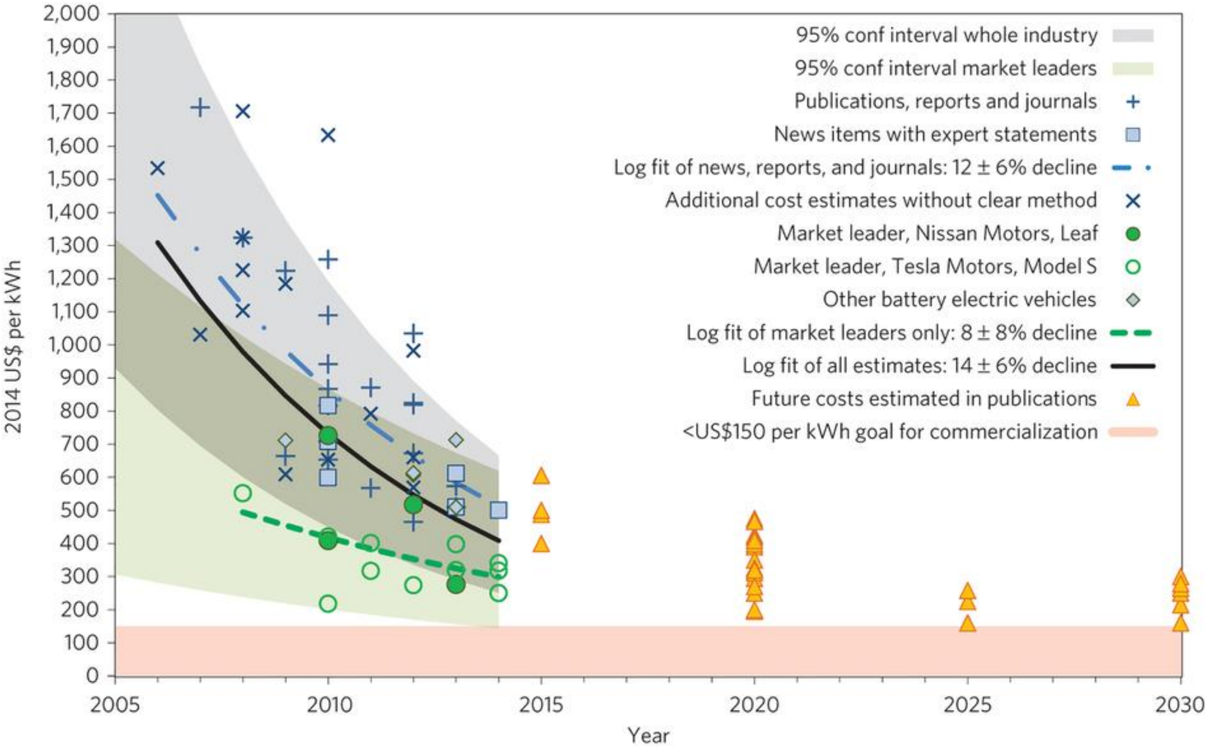

Figure 1: The falling cost of lithium-ion batteries [12]

Considering the difference between the current costs, the required cost targets and the need for manufacturing scale up, the UK automotive council has outlined a technology roadmap for low carbon passenger vehicles [13] as shown in Figure 2. Here it can be seen that in order to transition to a full BEVs, micro/mild hybrids will be the first introduced technology to improve fuel economy of ICE vehicles. Full hybrids and plug-in hybrids whereby the size of the battery increases with the ICE downsized to become a range extender is then seen as the next horizon. Finally, it is forecasted that the EV charging infrastructure will eventually be developed, allowing for mass market penetration of BEV technology.

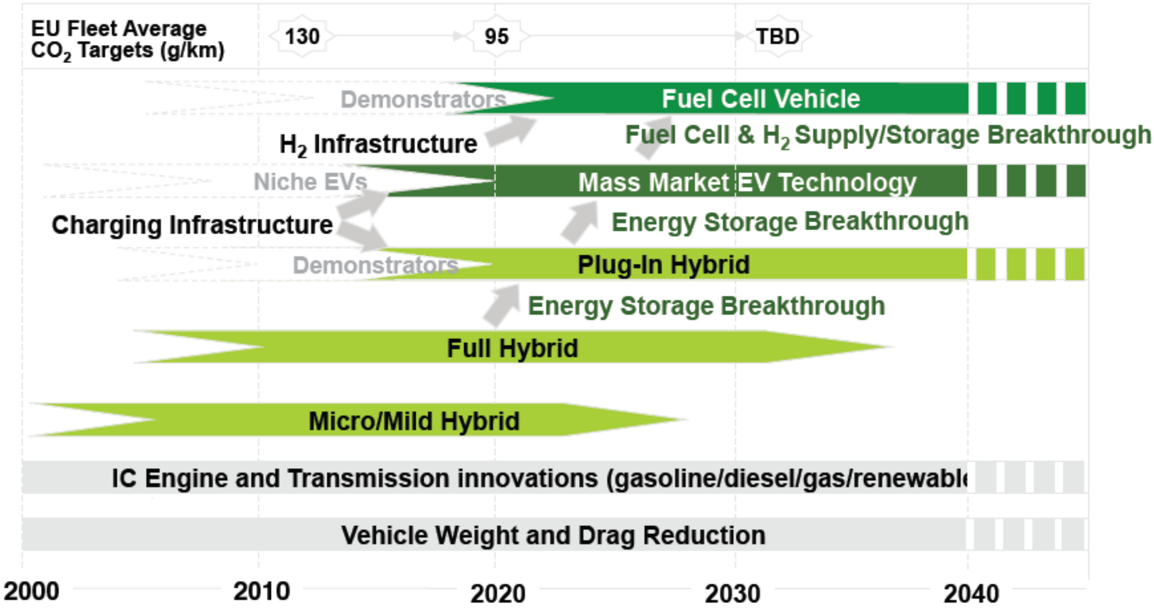

Figure 2: Passenger car low carbon technology roadmap [13]

Alongside technology shifts, a common theme will be vehicle weight reduction. For ICE vehicles, there is a strong correlation between vehicle weight and fuel economy [14] which is well known. However, whilst weight reduction will always be beneficial to improving the fuel economy, the correlations differ for BEVs, HEVs and FCVs. For BEVs and HEVs, the ability to recover a large proportion of the kinetic energy through regenerative braking mitigates some of the importance of weight reduction. Pure FCVs on the other hand cannot recover this kinetic energy and thus the importance of weight reduction is much more significant. Nevertheless, research and development in battery weight reduction is an active and important area. This will likely come about through 3 main routes: innovations in battery chemistries, improvements in battery pack designs and more intelligent use of the energy storage system.

- **Battery chemistry innovations** – Improvements in battery materials is one of the main drivers behind the progression of BEVs from the early days of milk floats with lead acid batteries to the Tesla Model S with lithium-ion batteries. The majority of current lithium-ion batteries use a graphite anode combined with a cathode commonly composed of a combination of nickel, cobalt and manganese. Near term improvements in energy density will be achieved through optimisation of these chemistries; however medium term energy density gains are envisaged to come about through the use of silicon anodes [15,16], sulphur based cathodes [17,18] and nickel-rich layered oxide cathodes [19]. In the long term, the application of metal-air batteries such as lithium-air [20] and zinc-air [21] shows promise; however poor lifetime and efficiency remain challenges. In terms of the environmental impact of producing these new battery chemistries very little has to date been reported.
- **Improvements in battery pack design** – Often when discussing battery technologies the energy density of the material is cited however once the materials are integrated into a cell, the gravimetric energy density decreases due to the weight associated with inactive phases such as current collectors, binders, separators and packaging. Integrating a cell into a pack and system then incurs additional weight penalties through cooling systems, physical enclosures and electrical connections which can be substantial. Optimising these engineering aspects of batteries will inevitably result in

weight savings and better utilisation of the energy storage capacity which will impact the life cycle analysis of the system.

- **More intelligence use of the energy storage system** – Starting from the energy density of an individual cell and linearly scaling to a pack and including the additional mass of ancillary components does not necessarily result in the available energy. Often cell-to-cell variations [22] result in underutilised capacity to avoid over-charging and over-discharging a battery. In addition to the cell-to-cell variations, the full state-of-charge (SOC) range of battery is rarely used in automotive applications as it is often difficult to extract charge at low SOCs due to large voltage variations and increased cell resistance. Currently, extending these self-imposed operational limits are an area of active research [23,24].

It is generally acknowledged that HEVs and BEVs will be needed in order to achieve proposed emission targets. Yet, there are many challenges that need to be addressed before this is a reality and the environmental impact of the technologies needs to be fully understood. This chapter will review the current state-of-the-art with respect to automotive energy storage technologies, their application in hybrid and electric vehicles, discuss the influence of different load cycles, consider the life cycle assessment of the storage technology and consider any potential global warming potential of the technology.

2. Energy storage and conversion technologies

The progressive uptake of hybrid and electric vehicles has been underpinned by advances in energy storage technologies. These can come in various types, but in the context of automotive technologies, this has mainly focused on electrochemical technologies such as batteries and supercapacitors, though there are notable exceptions such as mechanical flywheels [25]. Whilst hydrocarbon based fuels are a form of energy storage, a key distinguishing feature of electrochemical energy storage devices are their ability to recharge on-board from the regenerative braking energy of the electric motors. This ability to recover waste kinetic energy can increase the fuel efficiency of the vehicle by 20-50% depending on the size of the motor and the drive cycle [26]. In addition, the electrochemical nature of the energy conversion means that higher efficiencies can be achieved over combustion based fuels which are limited by the Carnot efficiency.

In general, batteries are the energy storage technology most frequently employed in hybrid and electric vehicles. Whilst, supercapacitors and flywheels are also able to do so in theory, they are not practical as the prime mover for a vehicle due to their low energy density and therefore the extremely low range. This is except for a few unique examples, such as supercapacitors buses [27], which are likely to be a very specialised niche due to the infrastructure costs and requirement for regular timetabled stops for recharging. Therefore both flywheels and supercapacitors tend to be hybridised with another energy storage technology or conversion device to reduce transient loads [28].

An overview of different battery technologies considered for automotive applications is shown in Table 3. The earliest EVs employed lead acid based chemistries; however their low energy efficiency and energy density limited their more widespread use. In the case of lead acid batteries, whilst the lead is toxic, the recyclability is high. Nickel-cadmium (Ni-Cd) batteries achieved moderate uptake in consumer electronics however the toxicity of the cadmium and the memory effect associate with the chemistry ultimately limited its uptake. Nickel-metal hydride (Ni-MH) based batteries were the first chemistry to see appreciable commercial uptake in electric and hybrid vehicles however this is now transitioning to lithium-ion based chemistries due to superior energy density. Beyond lithium-ion there is extensive research on metal-air based batteries though lifetime and energy efficiency remain limiting problems towards commercialisation.

Table 3: Comparison of different battery based energy storage technologies for automotive applications. Adapted from Armand and Tarascon [29] unless otherwise stated.

Battery type and approximate period of use	Features	Environmental impact	Practical energy density (Wh/kg)
Lead acid (1859-1909)	Poor energy density, moderate power rate, low cost	Lead is toxic but recycling is efficient to 95%	37 [29]
Nickel-Cadmium (1909-1975)	Low voltage, poor/moderate energy density, relatively high cost, memory effect	Cadmium is a toxic heavy metal [30,31]. Nickel not green (difficult extraction/unsustainable), toxic. Not rare but limited recyclability	50-75 [31]
Nickel metal hydride (1975-1990)	Low voltage, moderate energy density, high power density	Nickel not green (difficult extraction/unsustainable), toxic. Not rare but limited recyclability	60-70 [32]
Lithium-ion (1990-present)	High energy density, power rate cycle life, costly	Depletable elements (cobalt) in most applications; replacements manganese and iron are green (abundant and sustainable), lithium chemistry relative green (abundant but the chemistry needs to be improved), Recycling feasible but at an extra energy cost	100-150 [33]
Zinc-air (Future)	Medium energy density, high power density	Mostly primary or mechanically rechargeable. Zinc smelting not green, especially if primary. Easily recyclable.	350-500 (1,086 theoretical)* [20]
Lithium-air (Future)	High energy density but poor energy efficiency and rate capability	Rechargability to be proven. Excellent carbon footprint. Renewable electrodes. Easy recycling.	Unclear (3,458 theoretical)* [20]

* Includes the mass of oxygen

As batteries are zero-emission at the point of use, the influencing factors which determine their environmental impact are the materials used in their construction, their disposal, the storage/conversion efficiency and how the electricity was generated. Toyota, who were one of the early adopters of hybrid and electric vehicle technology, used Ni-MH based batteries in their earlier Prius model range before recently transitioning to using more lithium-ion based chemistries. On a $kgCO_2eq$ basis, Majeau-Bettez et al. [30] showed that Ni-MH based batteries produced approximately double the emissions (considering production and use) compared with lithium-ion battery chemistries based on nickel-cobalt-manganese (NCM) and lithium-iron phosphate (LFP). This analysis however does not consider the environmental impact of the disposal.

Comparing and contrasting the different storage technologies can be problematic and often confusing. For example, there have been many attempts to compare hydrogen FCVs with BEVs on a like-for-like basis and there has been significant conflict between the two research communities over the years. Some have attempted to demonstrate their synergies [31] rather than use their differences to argue one technology is superior to the other for a one-size-fits-all solution [32]. However, comparisons are necessary and there are many papers and reports that compare these technologies with each other and the incumbents, often trying to predict a winner. This is fraught with difficulties, and it has been shown that the uncertainties in the assumptions used by most authors allow any technology to be predicted as the winner by carefully selecting the assumptions to predetermine the answer [33].

In recent years, it has become clear that vehicles powered by electricity stored in batteries are currently the front-runner to replace the ICE and liquid hydrocarbon tank, with hydrogen FCVs the next most likely contender, although there is still uncertainty over whether plug-in HEVs (PHEV) or BEVs will dominate. This is because vehicles with batteries have a head-start due to the presence of a mature lithium-ion battery supply chain capable of delivering the capacity needed by the automotive industry to scale up production quickly at a reasonable price. For example, the lithium-ion battery industry produced an estimated 35 GWh of cells in 2015 [34], from which the Statista service estimated the global lithium-ion battery market to be $9.8B. Assuming this is true, this means that Tesla with an average battery pack size of 80 kWh and sales in 2015 of 50,580 vehicles, bought 12% of the global lithium-ion battery production in 2015. Statista predicts the battery industry to grow to $15.6B by 2020, (CAGR of 60%) although they acknowledge this is a low EV uptake scenario, and others predict growth to anywhere between $30-40B [34]. Assuming costs reduce to 200 $/kWh, the upper estimate of $40B would mean annual production of 200 GWh/yr which represents a CAGR of 41%, but it is not known if the investment plans of the major battery producers are commensurate with these estimates. However, the gigafactory being built by Tesla and Panasonic alone will have the capacity to produce 35 GWh/yr by 2020 (equivalent to the production of the entire world in 2015). This factory alone would be enough to sustain the production of 437,500 Tesla vehicles a year.

In contrast, although fuel cell (FC) system costs are following a downward trajectory according to the US department of energy (DOE), and look likely to reach a cost of 90-160 $/kW by 2020, the actual cost for FC systems remains high. In 2016, FCs were estimated to be $24,000 for an 85 kW system, or $280/kW, assuming a manufacturing volume of 20,000 systems/year [35]. However, this is misleading, as they factored in a learning rate, when the knowledge learned through scaling up hasn't been done yet. In addition, this is still well short of the US DOE target of 30-40 $/kW they estimate is needed to be competitive with ICEs. FCs also lag behind batteries in terms of volumes. Global total cumulative FC installations reached 1 GW by 2014, with the global FC industry projected to install the next 1 GW by 2016/17 [36]. For comparison, 1 GW of FCs would be roughly 12,500 vehicles (assuming 80 kW stacks). This puts them roughly 10 years behind batteries in the number of vehicles the FC industry is likely to be capable of supplying.

3. Hybrid vehicles

There are several different forms of hybrid vehicles, however the fundamental concept is the combination of 2 or more power sources to provide tractive power to the vehicle powertrain, with the aim of providing combined benefits that neither system would be able to achieve in isolation. The often cited advantages of hybrid systems over their pure ICE counter parts include:

- Increasing fuel efficiency of the ICE by reducing engine transients and allowing it to operate at its most efficient point.
- The ability to recover regenerative braking energy.
- Reducing engine idling losses.
- Allowing for engine downsizing whilst maintaining total vehicle equivalent performance and thus reducing the frictional losses in the ICE.

Whilst there are many specific variations of hybrid vehicle configurations, there are 4 main classifications: series, parallel, series-parallel and complex hybrids [37]. These vary based on their control and configuration as shown in Figure 3. The environmental impact of the different configurations will have some variation due to increased efficiencies of one over another, however the most profound differences in emissions are due to the degree of hybridisation, which defines how much electrical storage is installed. Offer et al.[38] showed, for a FCV, that as the degree of hybridisation increased the average lifetime emissions from small to large vehicles decreased. However, as highlighted in Figure 4 there is a law of diminishing returns above a battery size of 5 kWh for small vehicles and 25 kWh for large vehicles. As the degree of hybridisation increased, it was also highlighted that to realise emission reductions, the decarbonisation of electricity was an increasingly important parameter as shown in Figure 4. Thus, electrification of road transport must also be accompanied by decarbonisation of the electricity generation in order to reduce WtW emissions.

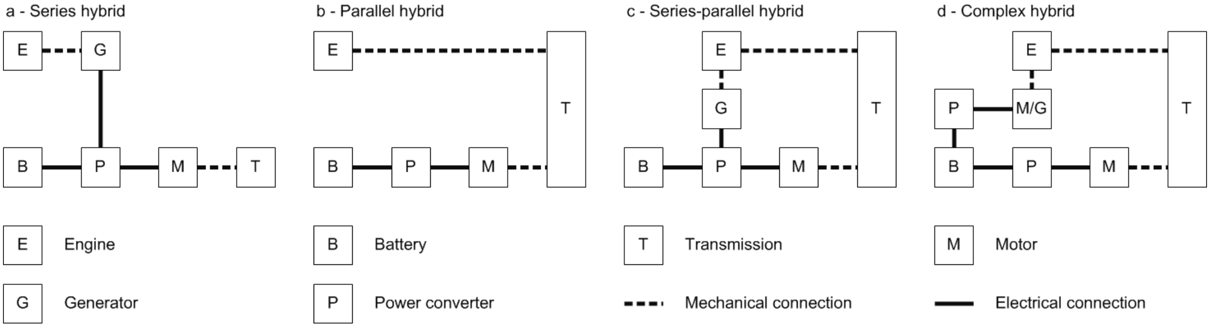

Figure 3: Different powertrain architectures adapted from Chan [37]

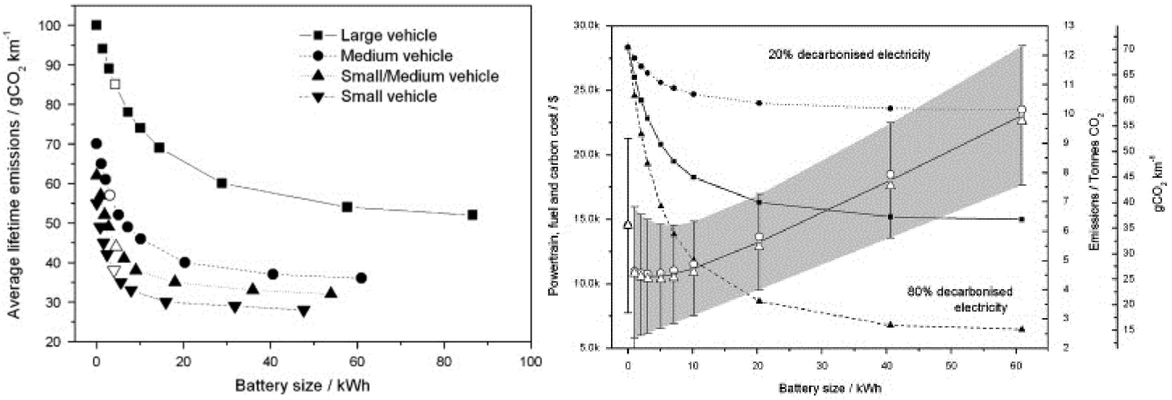

Figure 4: (a) The CO2 emissions for the different vehicle types shown in Fig. 13, large (■), medium (●), small/medium (▴) and small (▾). (b) Sensitivity to the extent of the decarbonisation of the electricity generation with electricity decarbonisation assumptions set low (○) and high (Δ). The carbon dioxide emissions are overlaid with the axis on the right and assumptions set low (●), average (■) and high (▴). [38]

In terms of the fuel consumption benefits of an ICE-hybrid vehicle, this varies depending on the vehicle, degree of hybridisation and load cycle. Fontaras et al. [39] tested a Toyota Prius II and Honda Civic IMA which are classified as full and mild hybrids respectively, under different load cycles. Results showed that the higher the degree of hybridisation the larger the fuel economy benefits under urban driving conditions. Above 60 KPH, the mild and full hybrids exhibited similar fuel consumption and above 90 KPH the fuel consumption was similar to that of the equivalent ICE vehicle. Under urban driving conditions, fuel consumption was found to be 40-60% lower than the average equivalent ICE vehicle. These benefits are enhanced for drive cycles with very low average speeds and frequent stop-and-go events.

4. Impact of different usage cases

One of the major challenges for automotive applications is the wide usage range which a vehicle needs to be designed for. Often this is captured and accounted for in the form of vehicle drive cycles, which are time-velocity traces which powertrains are validated against. The use of drive cycles in assessing the true fuel economy of a vehicle powertrain is often highlighted and shows significant differences compared to the application of “nominal loads” [40]. Andre [41] presented a comprehensive overview of different vehicle drive cycles with the aim of deriving a common set of reference real-world driving cycles. Here he showed 12 types of European driving patterns ranging from congested urban to motorway, steady speed. Typical metrics used to characterise drive cycles include average/peak velocity, duration, average acceleration and peak acceleration [41,42].

Whilst, the drive cycles presented by Andre [41] are indicative of real world driving, current automotive benchmarking is often performed with the New European Drive Cycle (NEDC) as an industrial standard. However, there are criticisms of this as it is not very indicative of real world driving conditions and thus there have been efforts to introduce other standard drive cycles such as the NYCC and HWFET (shown in Figure 5) which represent urban city driving and highway driving respectively.

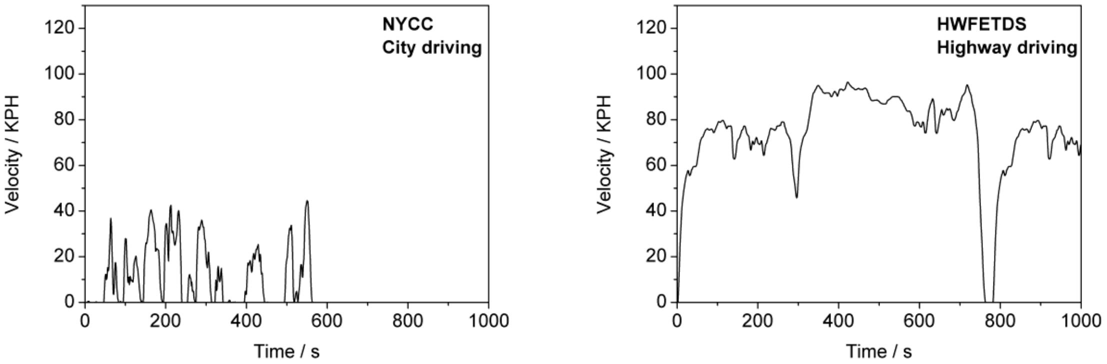

Figure 5: Time velocity traces representative of (a) urban driving (NYCC) and (b) highway driving (HWFET)

This can have dramatic effects on the fuel efficiency of vehicles and can change the optimum powertrain selection. For instance Karabasoglu and Michalek [10] analysed the influence of driving patterns on life cycle cost and emissions of HEVs. They showed that under urban drive cycles such as the NYCC, the life cycle emissions of a HEV can be 60% lower than a conventional ICE vehicle. In contrast, the same HEV was shown to have marginal emission reductions under highway drive cycles such as the HWFET.

By converting the time-velocity profiles into time-power profiles via a vehicle model and analysing the results, the differences in the energy/power requirements become even more apparent. Figure 6 shows histogram plots of the normalised cumulative energy requirements of the NYCC and HWFET drive cycles against the power. In the NYCC drive cycle it is apparent that a significant amount of regenerative braking energy is available. Here it should be noted that it is not always possible to recapture all the regenerative braking energy, especially at high power and low motor speeds due to charging limitations of the battery and inefficiencies in the motor/power converters under certain operating regions, respectively. In contrast, the HWFET drive cycle shows an insignificant amount of regenerative braking energy available due to increased air resistance dissipating the kinetic energy and also fewer deceleration events. Thus, for highway driving, the fuel economy benefits of HEVs is negligible, however for urban city driving these can be significant, in part due to the braking energy which can be recovered.

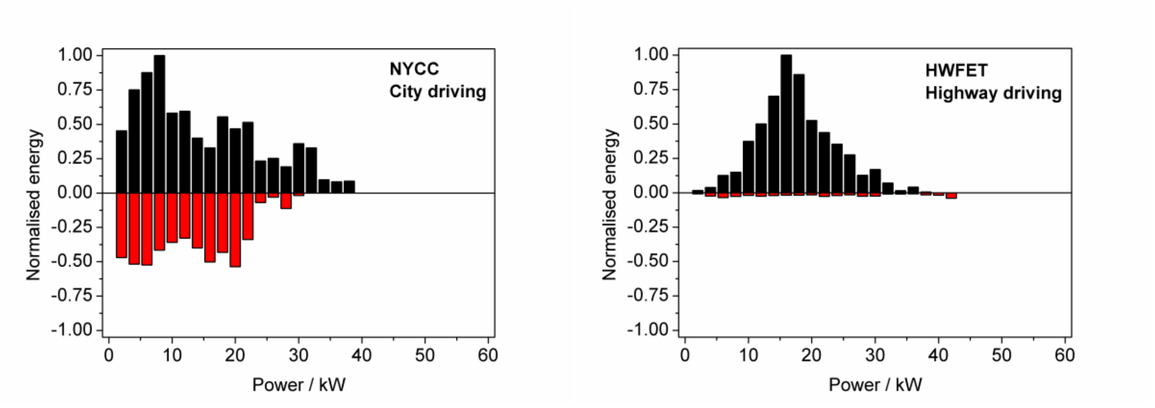

Figure 6: Histogram showing the normalised energy vs power for (a) the NYCC and (b) HWFET drive cycles [43]

5. Life cycle assessment (see also Chapter 9 for details of LCA methods)

With respect to the environmental impact of HEVs and BEVs, much of the academic literature has focused on WtW studies comparing fossil fuel and electricity use as it is often viewed that the in-use phase of the vehicle usage dominates the environmental impact [3]. For instance, Campanari et al.[40] conducted a detailed study into the WtW emissions of the various powertrains. Intuitively, the study showed that BEVs powered by electricity generated renewably offered the lowest emission option. However, when considering the BEV WtW performance with an average energy mix or 100% coal/natural gas, the performance was much lower. Here FCVs become much more favourable from the perspective of efficiency and CO_2 emissions, especially for vehicles with longer ranges due to the increased vehicle mass.

However, it would be unfair to disregard the energy consumption requirements of producing and disposing of the storage devices in the analysis. A recent review that looked at 79 life cycle analysis (LCA) studies on lithium-ion batteries [44], found that on average, producing 1 kWh of storage capacity was associated with a cumulative energy demand of 328 kWh and caused GHG emissions of 110 $kgCO_2eq$. However, they also concluded that although the majority of existing studies focus on GHG emissions or energy demand, impacts in other categories such as toxicity may be even more important.

The energy return on investment (EROI) is often used to assess energy production technologies, such as solar panels. However, batteries are fundamentally different, as they do not produce energy, they merely store it. Therefore, in order to calculate the EROI for a battery it is necessary to calculate the energy saved during operation of the vehicle as shown in Equation 1. For example, using the model developed by Contestabile et al. [33], if a HEV contains 2 kWh of batteries, and assuming the vehicle efficiency increased by 12% from 58 mpg to 66 mpg, with a lifetime mileage of 109,000, it would save over 10.5 MWh of energy over its lifetime, giving it an EROI of over 16.

Equation 1
$$EROI = \frac{kWh_{saved}}{kWh_{production}}$$

The same equation can be used for emissions by replacing kWh with $tonnesCO_2eq$, and assuming 3.0 $kgCO_2$ per litre for petrol. Thus, on a CO_2eq emission basis, HEVs would produce 3.2 $tonnesCO_2eq$ less, saving almost 15 times the emissions produced making the batteries.

The analysis for a BEV is slightly different. For the Nissan LEAF with a 24 kWh capacity, the battery manufacturing cost alone would amount to 7.9 MWh of energy and 2.64 $tonnesCO_2eq$. Assuming the same lifetime mileage of 109,000 and an energy consumption of 0.27 kWh/mile, it would save almost 54 MWh of energy over its lifetime, giving it an EROI of 6.8. Taking the 2.64 tonnesCO_2eq emissions due to battery production alone gives an equivalent vehicle emission of 15 gCO_2/km, which although low compared to most other vehicles is not completely zero and does vary depending on the electricity generation method. Thus, the claim that BEVs are zero emission is only true if both zero emission electricity is used both to recharge the vehicle and throughout every stage of the manufacture of the batteries and raw materials. In addition, this is not the full story, as there are other additional components such as electrical machines, power electronics which must also be taken into account.

A study by Notter et al. [45] showed that in a BEV, the lithium-ion battery production is only responsible for around 6% of the cumulative energy demand and 8% of the global warming potential over the lifetime of use. The rest of the car was shown to account for approximately 3.5x more, and the remainder was attributed to operations which were highly subjective to the local electricity production and the drive cycle. A more recent study by Ellingsen et al. [46] explored the effect of the type of electricity production in more detail, and the effect of vehicle size and mileage. They found that smaller vehicles and electricity produced by non-renewable sources had the greatest environmental impact and that the higher manufacturing impacts of EVs were compensated for by the lower environmental impact when using the vehicle, unless the electricity was produced by coal. If the electricity was produced by natural gas, the total vehicle mileage needed to be greater than 100,000 to be of benefit, but a total vehicle mileage of just 30,000 was required if the electricity was produced by wind. The review by Nordelof et al. [47] concluded that electricity production is the main cause of environmental impact for PHEVs. Using the assumptions from Ellingsen et al. [46], the energy efficiency of coal and gas fired electricity generation of 33% and 45% respectively, and the model of Contestabile et al. [33], Table 4 has been produced.

Table 4: Key energy metrics for different vehicle types.

	Lifetime Fuel Energy (MWh)	Battery Energy (MWh)	Battery EROI	Fuel Emissions (TonnesCO_2eq)	Battery Emissions (TonnesCO_2eq)	Battery CO_2ROI
Petrol	83.0	n/a	n/a	25.7	n/a	n/a
Hybrid	72.5	0.66	16.0	22.4	0.22	14.7
Electric Coal	88.1	7.9	-0.7	29.9	2.64	-1.6
Electric Gas	64.6	7.9	2.3	17.3	2.64	3.2
Electric Renewable	29.1	7.9	6.8	0.6	2.64	9.5
PHEV Gas	73.0	2.5	4.1	21.16	0.83	5.4
PHEV Renewable	54.3	2.5	11.6	12.4	0.83	16.1

It should be noted that the results in Table 4 are highly dependent upon the input assumptions, and therefore these results are only to be used as a qualitative comparative guide. Therefore, Equation 1 can be used for other vehicles, but the kWh_{saved} must take into account the energy displaced compared to a conventional powertrain, according to Equation 2.

Equation 2 $$kWh_{saved} = kWh_{conventional} - kWh_{alternative}$$

The effect of different electricity production and degrees of electrification can be seen quite clearly in Figure 7 taken from a recent review of the environmental impacts of HEV, PHEV and BEVs [47]. The sensitivity of BEV environmental impact to electricity generation source is perhaps the most important factor to consider. Hawkins et al. [3] for instance, suggested that in regions dependant on coal electricity generation, an increased trend in SO_x emissions was observed.

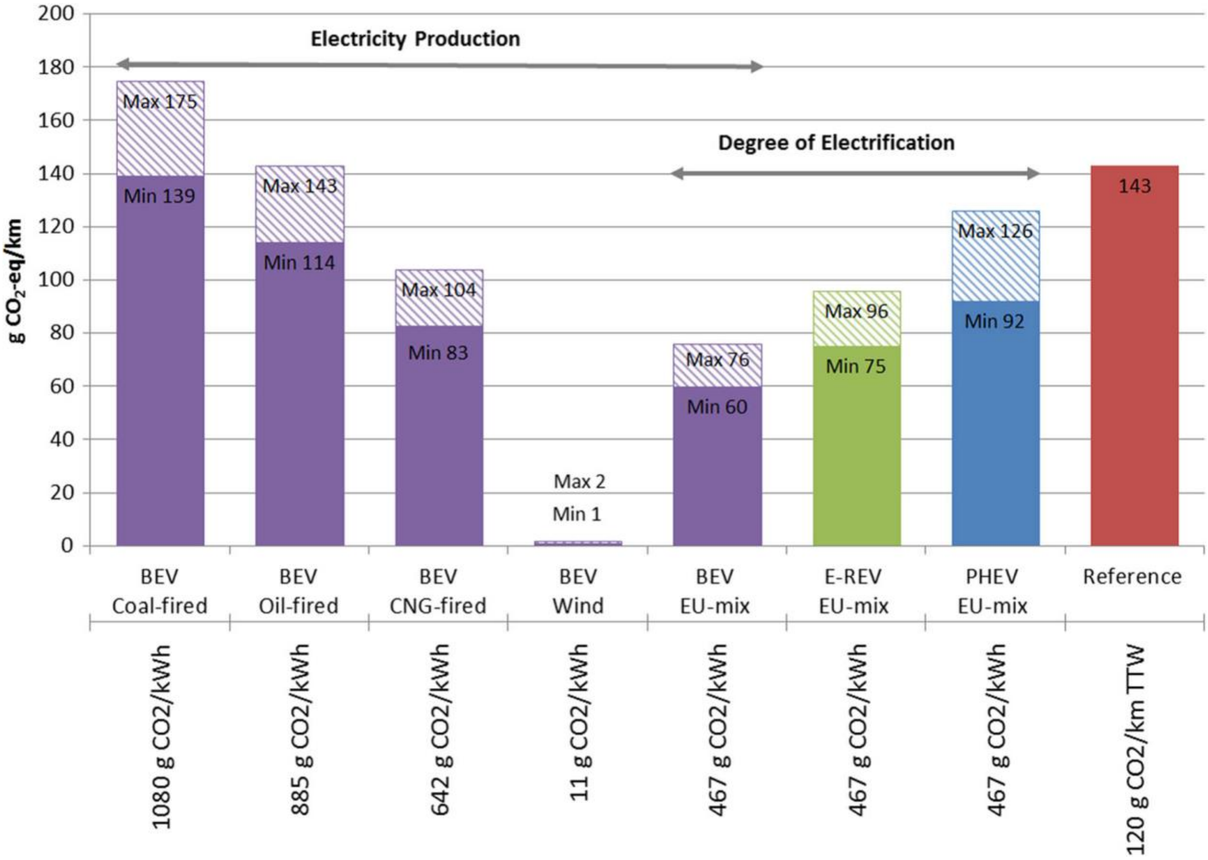

Figure 7: WtW GHG emissions for different electricity production and degrees of electrification [47]

5.1. Battery utilisation

Different vehicles use the batteries to varying extents, with hybrids often having a far greater utilisation than BEVs. The battery utilisation was shown by Contestabile et al. to be strongly affected by the size of the battery pack and the way that vehicles are used [33]. With current behavioural patterns, an average daily mileage of 20-30 miles can be met with a modest battery size between 5-15 kWh depending on the size of vehicle [38]. In contrast, the battery utilisation for larger battery packs in BEVs drops significantly, as shown in Figure 8. If the same total lifetime mileage is assumed this affects the result considerably, as the displaced energy kWh_{saved} will only increase slightly but $kWh_{production}$ increases considerably, as shown in Figure 9. This is why PHEVs have a far higher EROI and CO_2ROI than EVs as shown in Table 4.

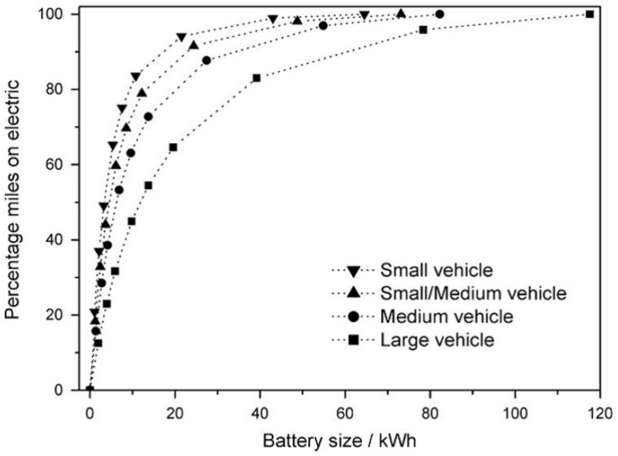

Figure 8: The percentage of miles that can be driven using electricity as a function of battery size according to current behavioural patterns, taken from [38]

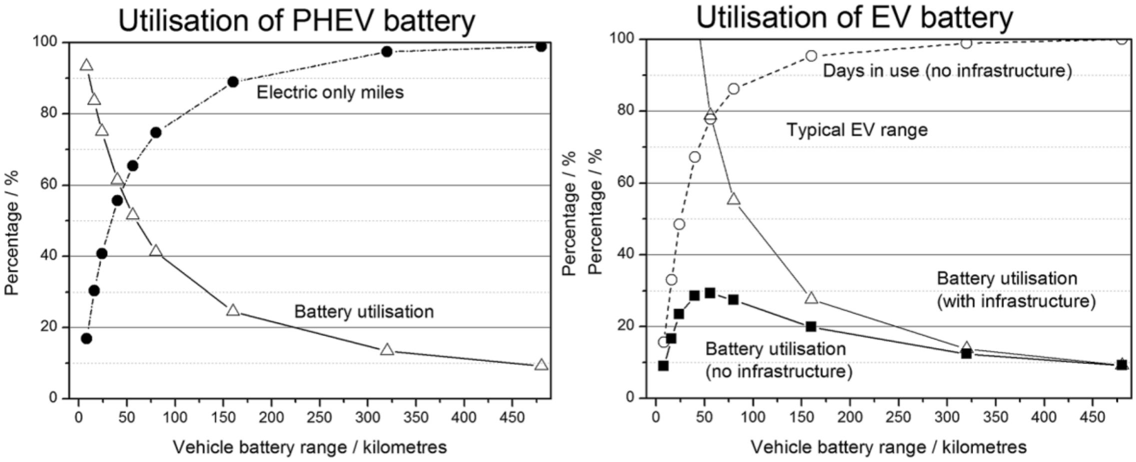

Figure 9: (a) Battery utilisation as a function of vehicle range for a PHEV also showing electric only range, and (b) for an EV with and without infrastructure (i.e. fast charging) also showing days in use when without infrastructure. Reproduced/adapted from ref. [48].

However, changes in business models and behavioural patterns, and/or the introduction of autonomous vehicles could change this again, and by increasing the battery utilisation, this makes BEVs more favourable again [48].

5.2. Vehicle-to-grid

Vehicle-to-grid (VtG) balancing involves, at its simplest, using smart meters to charge BEVs or PHEVs at a time that suits the grid operators. More advanced systems feed energy back from the vehicles into the grid at times of high demand, helping the grid operators balance the system. First proposed by Amori Lovins in 1995 [49], it has been discussed for many years [50,51] and it has been theorised as one of the ways to enable high penetrations of intermittent renewable electricity generation on the grid [50]. VtG technology is therefore one of the potential benefits of large scale electrification of vehicles, but this has yet to be demonstrated or implemented at a practical scale. There are also other challenges to overcome such as battery degradation, communication and changes to infrastructure [52]. However, if VtG technology can be implemented at scale this would improve the environmental impact of BEVs powered by non-renewable generation since there would be expected grid scale benefits to having balancing capability with respect to removing inefficient peaker plant generation. For instance, Sioshansi and Denholm [53] suggested that the introduction of VtG could potentially eliminate more than 80% of the CO_2 generated from of the additional generation required to support PHEVs.

5.3. Battery lifetime and degradation

In addition to the factors already considered, the lifetime of the battery pack i.e. the rate of degradation, is important. All the studies above either explicitly or implicitly assume that the battery pack will not need to be changed over the lifetime of the vehicle. In reality, some degree of degradation will likely occur and not accounting for this affect can have significant impacts on the environmental impact. For example if the battery needs replacing once in a vehicle lifetime, this will halve the EROI and CO_2ROI.

Another factor is the cycle life of the battery, which can be taken into account with a total lifetime energy throughput according to Equation 3.

Equation 3 $$kWh_{lifetime.throughput} = kWh_{capacity} \times cycles$$

This assumes that each cycle uses the full capacity of the battery, i.e. 100% depth of discharge (DOD). If this is not true then the Equation 4 can be used instead.

Equation 4 $$kWh_{lifetime.throughput} = kWh_{capacity} \times \%_{DOD} \times cycles$$

This is important, because the rate of degradation can often be significantly slowed down by reducing the depth of discharge of a battery [54], and hence the $kWh_{lifetime.throughput}$ can be increased by changing the way the battery is used. This is done in most HEV applications to extend the life of the battery, and to a lesser extent even in BEVs. The $kWh_{lifetime.throughput}$ can also be helpful when trying to take into consideration second life applications.

5.4. Recycling and second life

Whilst the materials used in the construction of lithium-ion batteries are finite, it is unlikely that the adoption of BEV and HEV technology in the future will deplete global reserves [55]. The lithium content of a lithium-ion battery only accounts for approximately 0.7% of the mass and the current extraction process from brines are relatively simple and have a low energy demand [45]. Yet, recycling is necessary to reduce the impact on base material mining such as aluminium, copper, cobalt, manganese and nickel. If not considered, this has both an economic, energy and emissions cost, decreasing the EROI and CO_2ROI. Second life batteries can have both an economic benefit, and increase the $kWh_{lifetime.throughput}$, resulting in an improvement on the EROI and CO_2ROI.

Therefore, wherever possible, second life should be considered before recycling though challenges for real world implementation include screening and matching of cells with consistent characteristics [56]. Manufacturers of HEVs and BEVs often suggest battery replacement when the remaining energy capacity reaches 70-80% [57] meaning useful capacity still remains at the point of disposal for transport applications. However, it has also been highlighted that the point of replacement is different for BEVs and HEVs. For instance, Wood et al. [58] highlighted that fact that PHEVs can blend the delivered power meaning that performance can be maintained at the slight cost of efficiency. Thus, battery replacement should only be considered if there is a significant improvement in the performance/efficiency. BEVs are not able to blend power delivery and thus the end-of-life point will often be at a higher remaining capacity. Despite some exploratory works into second life batteries there are few detailed studies into their environmental impact due to the variability of degraded cells. Thus, technical barriers such as estimation of degradation [59], practical diagnostic techniques [60–62] and economic incentives are required [57] before second life batteries are implemented at scale.

With regards to recycling of lithium-ion batteries there has been slightly more work though not extensive regarding the environmental impact. A recent study by Oliveira et al. [63] confirmed again that the use phase dominates the impact, but also showed that the recycling stage can be just as important as the manufacturing stage in terms of environmental impact, as shown in Figure 10.

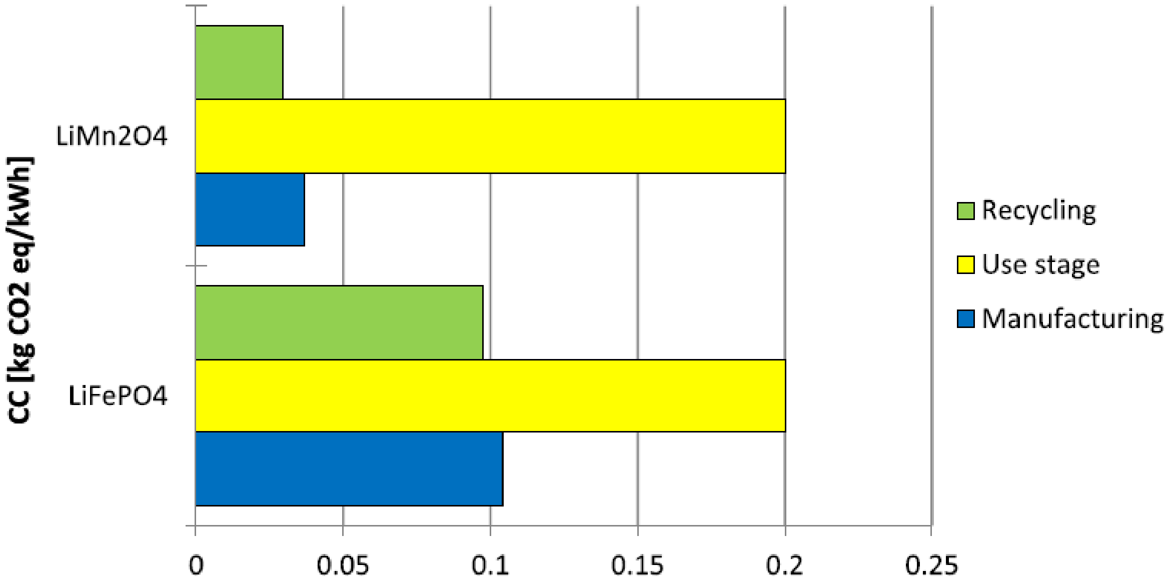

Figure 10: Climate change impacts of two common lithium ion batteries including recycling, use and manufacturing [63]

Dunn et al. [64] concluded that avoiding or reducing SO_x emissions and water contamination from the metals recovery for cathode materials should be the key motivator for lithium-ion battery recycling regardless of the energy intensity of assembly.

However, of concern is that a recent review of recycling methods concluded that most of the research achievements are still only in pilot or laboratory scale and that there is still a need to establish firm collection systems, large scale treatment plans and legislation covering the life cycle of lithium-ion batteries [65]. For example, in China only 2% of non-lead-acid battery waste is properly disposed of and most is simply dumped in landfills or piled in warehouses. Gaines [66] concludes that recycling automotive batteries is more complicated and not yet established because few end-of-life batteries have needed recycling and it won't be another 5-10 years before large numbers reach their end-of-life. However, despite this there is a need to act now to put in place economic and sustainable options for recycling. Gaines [66] also describes the many problems with lithium-ion batteries entering the current lead acid waste streams, causing problems such as fires and explosions at lead smelters.

6. Conclusion

It is undeniable that in order to achieve global GHG emission reduction targets, hybrid and electric vehicles must be implemented. However, transitioning from ICE based powertrains to electric will require further improvements in technology and cost reductions. In the near term, the environmental benefits of hybrid vehicles have been shown to be greater than that of pure BEVs in the majority of regions. This is due to the large proportion of coal and gas power generation in regions offsetting the benefits of the local zero-emission characteristics. In the case of a purely coal powered electrical network, the net CO_2ROI can actually be negative. However, it is also important to consider that the relative benefit is also highly sensitive on the usage cycle, with HEVs showing significant fuel economy gains of 20-50% in urban driving modes, but limited benefit in highway driving due to the significantly reduced amount of regenerative braking energy available.

High utilisation of the battery aids with the environmental benefits assuming a net positive CO_2ROI. It has been suggested that the implementation of VtG technologies can offset the additional CO_2 associated with the increased generation requirements of EVs by more than 80%, however this is yet to be significantly implemented. In the longer term, BEVs will have more environmental benefit, but relies on the energy mix of a region shifting toward renewables. The results of various works thus suggests that the electrification of transport needs to be accompanied by shifts in electricity generation to more renewable sources to avoid being counterproductive.

Research efforts into the environmental impact of lithium-ion battery production suggest that this is only approximately 6% of the lifetime energy consumption of a BEV with the majority dictated by the in-use phase. Whilst the common perception is to consider the impact of lithium in the battery, this only accounts for approximately 0.7% of the mass and consideration of elements such as copper, aluminium, cobalt, manganese and nickel are more important. The area of energy consumption during production is reasonably well researched however research into lithium-ion battery recycling is much more limited, but the few studies conducted suggest that the environmental impact could be on the same order as the production, however this is not yet conclusive. Second life batteries have been shown to have more of a positive environmental impact than recycling at the end-of-life for EV batteries. However, trials have been few due to challenges in estimating degradation, manual screening processes and limited economic incentives.

It is therefore clear that the current status of BEVs and HEVs is a long way from truly zero emission, and this should therefore catalyse efforts in producing renewable electricity, producing hybrid & electric vehicles and establishing suitable supply chains and policies to handle end-of-life batteries.

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