Energy Efficiency in EV/PHEV and its Impact on Total Cost of Ownership (TCO)

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Abstract

There is an increasing awareness, policies and an incentive landscape, which are encouraging and starting to shape future transport to be seen as part of a wider ecosystem of infrastructure, use, behavior and sustainability. However, one of the main barriers for the wider uptake by both fleet and individual users of electric vehicles is the concern of the uncertainties of Total Cost of Ownership (TCO).

This contribution, based on a mix of original modelling, simulation and laboratory experimentation studies as well as a review of the academic and policy literature, will focus on vehicle design and the battery and energy management in the EV/PHEV. EV users express concern about the longevity of the electric battery and hence the life cycle (especially with frequent fast charging), which amounts to a major part of the costs and value of the vehicle. Using the battery to provide ancillary services will add more value to the EV and reduce the effective TCO.

1 Introduction

The growing requirement to produce increasingly more energy efficient ultra-low carbon vehicles (ULCVs) represents a major technical and financial challenge for major vehicle manufacturers and component suppliers. Some of the current limitations of battery technology in terms of energy, density, power density, weight and cost [1] have led automakers to focus not only on the development of electric and hybrid powertrains but also on the optimization of other critical vehicle technical areas aimed at enhancing the vehicle overall energy efficiency, such as reducing the weight and drag [2]. The use of on-board ancillary systems (heating, lights, etc.) - in addition to the driver's driving style, vehicle speed and the type of journey - are also key factors to improve the vehicle energy efficiency, range and performance [3].

This chapter provides an overview of the main vehicle design advancements to increase Electric Vehicles (EVs) and Plug in Hybrid EVs (PHEVs) market penetration by offering vehicles with an increased range and consequently becoming a more attractive business proposition to prospective buyers or users. Some key technical constraints are also discussed as EV and PHEV technology is not at a mature stage yet [4]. In addition, an account of the design and operation of the battery, smart charging, eco-driving, vehicle energy consumption and management are provided. Finally, this chapter presents an evaluation, based on modelling, simulation and laboratory experimentation studies, on how these may be designed to lower the total cost of ownership (TCO), since this is critical for take-up.

2 EV/PHEV design to reduce energy demand during driving conditions

2.1 EV/PHEV Body Aerodynamics

Aerodynamics plays a prominent role in the overall efficiency of a vehicle. Most of the EVs and PHEVs available on the market feature an optimised aero package specifically designed to lower their *drag coefficient* (Cd) caused by airflow turbulence. It is common for vehicles such as the Toyota iQ EV to feature aerodynamic enhancements applied to the front grille opening and body panels to separate and improve air flow, as well as underfloor covers to minimise turbulence [5].

Similarly, the 2013 Fiat 500e low-volume EV is characterised by a reshaped front and rear end, revised wing mirror covers, small spats on the wheel wells, and under-trays to even out airflow [6, 7]. Aero improvements are also applied to some Internal Combustion Engine (ICE) vehicles in the shape of the special low carbon edition models, badged for instance *Blue efficiency* [8] by Mercedes-Benz, or *DRIVe* [9] by Volvo. From a comparative analysis, shown in Table 1, it follows that EVs and PHEVs are marginally more aerodynamically efficient than their ICE based counterparts.

Table 1. Vehicles' Cd comparison between ICE models and derived LCVs models [7,8,9,10,11,12,13]

Make	*Model*	*Drive*	*Year*	*Cd*	*ΔCd*	*ΔCd%*
Fiat	***500***	ICE	2007-present	0.36		
	500e	EV	2013-present	0.31	-0.05	-13%
Honda	***Mk7 Civic Sedan***	ICE	2001-2005	0.30		
	Mk7 Civic Sedan	Hybrid	2003-2005	0.28	-0.02	-6%
Scion	***iQ***	ICE	2008-present	0.31		
(Toyota)	***iQ***	EV	2012-present	0.31	0	0%

This trend generally applies to the latest breed of EVs and PHEVs which have been designed as electrified ULCVs right from the outset rather than being derivative versions of their existing ICE models. However, the latest BMW i3 and Nissan Leaf feature low drag bodies which are not significantly better than ICE vehicles of their respective size. The compared Cd figures suggest that some of the latest ICE models perform surprisingly well against the most evolved EVs available on the current market.

Table 2. LCVs Cd comparison [10, 14, 15, 16, 17, 18]

Make	*Model*	*Drive*	*Year*	*Cd*	*ΔCd*	*ΔCd%*
Honda	***Mk1 Insight***	Hybrid	2000-2006	0.25		
	Mk2 Insight	Hybrid	2010-present	0.28	+0.03	+12%
Toyota	***Mk2 Prius***	Hybrid	2004-2009	0.26		
	Mk3 Prius	Hybrid/ PHEV	2010/12-present	0.25	-0.01	-4%
Nissan	***Mk2 Note***	ICE	2013-present	0.30		
BMW	***i3***	EV	2012-present	0.29	-0.01	-4%
Mercedes Benz	***Mk2 B Class***	ICE	2012-present	0.26		
Nissan	***Leaf***	EV	2011-present	0.29	+0.02	+8%

Although there are some after-market PHEVs aero body kits such as the Aero Prius YuraStyle [19, 20], for the Toyota Prius, those designs are too extreme in terms of styling to be accepted by the vast majority of Prius owners [18]. Allegedly their improved Cd figures, obtained by further covering of the car rear end and wheels [21], may provide some tangible gain in terms of the vehicle extended range [20, 22] compared with the standard PHEV model, driven in everyday variable driving conditions.

2.2 EV/PHEV Kerb Weight

Air friction is not the only key parameter responsible for reducing vehicle range. The overall car kerb weight is another major technical challenge for auto makers as they aim to lower the vehicle mass as much as possible.

The lithium-ion traction battery in the Tesla Roadster weighs about 453Kg [23]. However, designers managed to offset the battery weight with the adoption of a full aluminium frame and plastic body panels to keep the EV car weight down to 1220kg [24]. This valid technical approach normally proves to be more costly when it is applied to conventional ULCVs designed for daily use.

However, there are different approaches towards increasing the vehicle range and efficiency of ULCVs. Chevrolet managed to increase the range of its Volt PHEV by reducing its aerodynamic drag which can be advantageous when regaining energy through regenerative braking [25]. BMW adopted a radical design of the i3, which is the first mass-produced vehicle in the world to feature a carbon-fibre reinforced plastic (CFRP) body structure [26, 27]. It is likely that future LCVs will also make use of this new chassis construction method as a common platform onto which an aluminium frame is mounted to house the battery and powertrain.

In the typical daily use of an EV/PHEV, predominantly in an urban environment, where low speed limits are enforced, the vehicle gross weight counts more than its drag. In simple terms energy calculations can be easily deducted from the following Newton's inertial force equation [28]:

$$F = m\ a \tag{1}$$

Where F is the Force needed to move the ULCV; m is the mass of the ULCV; and a the vehicle acceleration. If the mass value increases more force will be then required to obtain a given acceleration. This is why urban driving is less energy efficient than driving on motor ways, where acceleration is reasonably constant. In a different driving situation, e.g. an ULCV driving up a gradient is heavily affected by its weight, therefore reducing its driving range. For the above-mentioned conditions a lightweight ULCV is preferable. On the contrary, the increase in weight has its benefits after the ULCV acquires a certain speed, which is being kept reasonably constant (e.g. driving on a motorway) as the vehicle will carry more momentum (kinetic energy) to move along.

In the case of an ULCV used primarily for journeys beyond the city boundaries, at higher speeds, typically above 50 mph, the vehicle air drag begins to affect the amount of power required to propel the vehicle forward and maintain or increase its speed. This is due to the fact that [29]:

$$F = \frac{1}{2}\rho v^2 \, Cd \, A \tag{2}$$

Where *F* is the drag force needed to move the ULCV; ρ is the air density, *v* the velocity, *Cd* is the coefficient of drag, and *A* is the vehicle cross sectional area.

Assuming that ρ , *Cd* and A are constant (a specific vehicle), the change in the drag force (F) that results from a small change in vehicle velocity can be derived as:

$$\frac{\Delta F}{\Delta v} \approx \frac{\partial F}{\partial v} = 2\,(\frac{1}{2}\rho \, v \, Cd \, A) = 2\left(\frac{F}{v}\right) \tag{3}$$

which gives:

$$\frac{\Delta F}{F} \approx 2\frac{\Delta v}{v} \tag{4}$$

That is, a relative change in vehicle speed results in twice the relative change in the drag force needed to move the vehicle. This means that every time the vehicle speed doubles, the drag force value quadruples [29] as the amount of energy (Wh/mile) absorbed in aerodynamic losses. The other variable that greatly affects the ULCV range is the Cd, which depends on A. Thus, a low drag ULCV is the better option. With existing EV/PHEV battery technology, the increase in battery capacity, to extend the EV range, results in a larger battery mass and heavier vehicle [30].

It is foreseeable that in the future EVs/PHEVs will feature more sophisticated on-board control which will be able to optimize the ULCV efficiency and range using satellite navigation and maps to predict the vehicle journey continuously taking into account all the factors mentioned above. The ability to inform the driver of the vehicle's real time consumption also taking into account the wind speed and direction through constant updates from the Met Office, for instance, are part of the overall energy optimization which will be likely to be introduced in future ULCVs. Even apparently negligible power gains still have a significant summative effect on the overall performance of the vehicle.

2.3 EV/PHEV on-board or off-board charging

Today's battery technology constraints have led automakers to produce the majority of EVs with a limited range similar to the pioneering EVs produced in 1910 [31]. This, in addition to cost and charging which still presents a number of obstacles [32], are the main factors limiting the proliferation of EVs and PHEVs.

On-board charging enables EV/PHEV users to plug their cars in any domestic socket [33] or a power supply in various locations that are not necessarily in the proximity of a public charging point. However, Level 1 AC charging, running on 110V in the US, means that a PHEV/EV could take from 6+ hours (for a PHEV) to 24+ hours (for an EV) to charge [34]. The answer would be to upgrade to a Level 2 AC charging station, employing 220V supply, installed at home or nearby, to allow a PHEV to be charged from 2+ hours to 8+ hours for an EV [34]. This facility is also appropriate for charging vehicles at work, around shopping centres and supermarkets.

The very latest edition of the Nissan LEAF makes on-board charging more compatible with today's frantic lifestyle as its battery can be refilled within 4 hours through the adoption of a dedicated 6.6 kW charger option powered by 32 A circuit [36]. In order to further reduce 'filling up' times, Level 2 DC charging has been introduced which uses an off-board charger. The off-board charger is rated between 20 kW and 80 kW, which gives 3-5 miles' range for every minute of charge [34]. Fast chargers are expensive to install and therefore are not used for domestic charging; rather, they are popular for public and commercial charging stations.

Another viable solution to facilitate the use of EVs is represented by the concept of swapping the battery at a charging station, though the recent financial collapse of BetterPlace appears to be related to both the fact that Original Equipment Makers (OEMs) of EVs do not seem to be willing (other than Renault in this case) to standardise their batteries in an easy and cost efficient manner, and that some governments (Israel in this case) insisted on large-scale and extensive initial infrastructure investment.

3 Demand from Auxiliary (Non Power Train) Loads/Functions

Ancillary systems constitute an additional power load on the running of an EV and PHEV [39] which can significantly affect the range of the vehicle in various operating conditions. Typical functions as climate control (heat ventilation, air conditioning (AC)), lights, info entertainment (radio, CD player, centre console display, satellite navigation, etc.) are to be accounted as they can reduce the PHEV/EV travel range. The battery management system (*BMS*) and other primary auxiliary circuits (instruments binnacle electronics, central locking, electric windows, immobilizer, etc.) used to govern vehicular operations, add an imperceptible energy demand. This auxiliary power demand ($P_{Aux.\,Load}$) may be represented as:

$$P_{Aux.\,Load} = P_{AC} + P_{Lights} + P_{Info\,Entert.} + P_{BMS} + P_{Aux.\,Circuits} \quad (5)$$

The first three variables are particularly relevant to an EV as its driving range depends only on the main battery pack whereas a PHEV rely on an ICE unit to extend its range. An electric air conditioner with a peak load of 3 kW can reduce the EV range by 16-38% depending on the driving cycle [40]. Its power absorption may vary between 0.2-2.2kW. To compensate for such a power drain the latest 2013 Leaf adopts a new heat pump-based heating system, which is designed to use considerably less battery power [41].

The combined effect of internal and external lights is about 80 W [39] as efficient LED lights, used for turning signals, daytime running lights or brake lamps [42] are increasingly replacing traditional automotive bulbs and are commonly coupled with halogen and xenon headlights. In terms of audio equipment, manufacturers try to considerably reduce the auxiliary power consumption [43]; for example, the 2013 Nissan Leaf features a new premium Bose Energy Efficient audio [44] which uses about half of the electrical current than standard systems [45] whereas the Toyota Prius is fitted with a 120 W audio system that is comparable to 600 W systems [44]. The power consumption of BMS units, which consume on average between 15-40mA (3-8 W) [46, 47], and all other auxiliary electrical systems is negligible.

The overall power consumption of EV ancillary systems is 10-33% of the traction battery power, depending on the driver’s choice and use of heat or air conditioning [48]. To compensate for such a load, an EV may be equipped with photovoltaic panels, where a 200 watts system returns about 1 km of electric range for each hour of full direct sun exposition [49].

Future LCVs will be adopting a 42 V electrical system standard [53] in order to save weight and cost of the electrical components and improve energy efficiency. Manufacturers like Audi are planning to implement high voltage technology on 48 V mild-hybrid platform [54] in the short term.

4 Battery Cycle Life and State of Health

The battery is the most expensive part in an EV and accounts for over 50% of the total production costs of the vehicle [55]. Current EVs/HPEVs are usually powered by high capacity Lithium ion batteries, which vary in size from few kWh to few tens of kWh capacity. The battery capacity determines the vehicle electric range and, with current battery technologies, this is limited to around 200 km or less for commercial EVs/PHEVs. These two factors (cost and range) emphasize the importance of maintaining the battery in a healthy state for as long as practically possible in order to reduce the TCO.

Another area that will help reduce the TCO of EVs/PHEVs (with market growth and high deployment) is their use to support the grid. This can be in their use as a controllable load during charging or as storage in what is called Vehicle to Grid (V2G), where the EV could be used to store surplus output from renewable generation and release this back to the grid during peak demand [56-58]. Such application requires appropriate control and communication with the grid, vehicle user and battery management system [56] and may be implemented as part of the 'smart grid' concept [59]. However, providing this service by the EV/BHEV has negative impact on the battery cycle life and consequently on the vehicle TCO.

Battery State of Health (SOH) is defined as the difference between the usable capacity and the end of life capacity and is usually expressed as a percentage of the rated capacity [60]. EV manufacturers define the end of life capacity of the battery as the state when the battery capacity reaches 80% of the rated (fresh) capacity [60]. Therefore, it is important to understand the factors that affect battery degradation and provide the means to optimize battery SOH, not only reduce the TCO but also conserve vehicle range. Battery performance depends not only on the battery chemistry but also on external factors, such as surrounding temperature and the way the battery is being used. Capacity loss in Lithium-ion batteries may be attributed to two reasons: "calendar life" loss and "cycle life" loss.

The calendar life is the continuous slow degradation of the battery due to the passage of time, whether the battery is being used or not. It is largely affected by the storage temperature and the charge state. Extreme ambient temperatures and high average State of Charge (SOC) result in fast degradation. This type of degradation can be attributed to permanent chemical change and thus follows Arrhenius law [61]:

$$\frac{dC}{dT} = Ae^{kT} \tag{6}$$

Where T is the absolute temperature, C is the battery capacity. A and k are numerical constants that depend on battery chemistry and are usually determined by experimental tests. The cycle life depends on the chemistry of the battery as well as the way the battery is being used during charging and discharging. It is affected and hence determined by four main factors which are interlinked. These are: the charging/discharging current rate, battery temperature, SOC and depth of discharge (DOD). The significance of each parameter and its impact on the cycle life is usually estimated through experimental cycling tests, with varying accuracy. Usually, degradation caused by cycling is much faster than that caused by calendar loss (storage), but obviously this depends on the EV (battery) usage.

Test results show that battery cycle life drops with increased charging/discharging current rates, e.g. if the current rate goes up from 0.74 C to 1 C, the battery cycle life drops from around 1,000 to around 200 [62]. Test results demonstrate that Lithium ion batteries perform best and have a longer cycle life at room temperature around 20–25 °C [63]. They also perform better at low (less than 50%) average SOC. For example, the battery cycle lifetime when cycled at 15% SOC is over 3 times the cycle lifetime with a SOC of 95% [64]. Test results also show that at fixed temperature and current rate, the battery cycle life decreases with increasing DOD. For example, if battery capacity is fully used (100% DOD), the battery capacity drops to 80% of its initial value after 1600 cycles. When the DOD is 30% or less, the battery cycle life increases significantly to 10000 times [65].

Since different parameters that affect battery degradation (both calendar and cycle lives) are interlinked, it is difficult to exactly quantify the individual impact of these parameters. However, test data available provide valuable insight into the impacts and therefore help in the design of battery management systems and charge/discharge controllers that will optimize battery SOH.

As mentioned earlier in this section, battery degradation also depends on battery technology (chemistry) and this is continually improving and, together with appropriate control, can help in prolonging battery life and reducing the TCO of the EV/PHEV.

5 Smart Battery Charging

Smart charging is a crucial element in the realization of a safe, adaptable and sustainable power network which is able to cope with an increasing numbers of EVs and PHEVs constituting an additional energy load on the grid. An adequate control and management of charging is necessary to avoid poor power quality and possible electricity supply failures which can occur with high penetration of EVs [66]. Research has shown that network voltage levels may deviate from the statutory limits even with small penetration levels, say 10%, in weak parts of the distribution networks [67]. In addition, charging at peak demand on the grid would result in higher CO2 emissions and electricity rates [66].

The adoption of smart charge controllers that initiate and stop charging in relation to the conditions of the power grid [68] can minimise the impact of charging on the grid and minimise electricity expenses for EV or PHEV users. Smart charging may be designed to optimize EV and PHEV battery State of Charge (SOC) and calculate in real time appropriate charging patterns based on battery state of health and local power distribution voltage [68], taking into account the user's request. This complex operation can only be performed by a smart controller which also stabilises the grid by monitoring the incoming AC voltage, and frequency. In order to meet EVs and PHEVs deployment targets governments need to develop a concurrent network of rapid charging facilities and ensure that the energy network providers involved are fit for purpose when it comes to coordinating their services. By 2020, countries that are members of the Electric Vehicle Initiative (EVI), established by the International Energy Agency (IEA), have set cumulative targets to install about 2.4 million slow chargers and 6,000 fast chargers [68]. This infrastructure expansion through the mass adoption of smart controllers provides an opportunity to incentivise customers with different tariffs throughout the day and influence their charging behavior whilst maintaining the grid power management dynamic and balanced.

Energy generation in the future will rely more on renewables, where customers will decide to invest in PV panels, wind turbines or other low carbon generation technologies to produce part or all of their domestic electricity needs. This scenario will become reality, when the next generation of EVs, fitted with more powerful batteries, will be introduced to coexist and exploit the use of small-scale electricity generation from low carbon technologies. These vehicles will be capable of storing power to assist the grid balance and stability which becomes a problem with high penetration of intermittent renewables power generation [69]. At the heart of this system is the smart charging controller, which will provide an active and reliable control to support the network operation (offset voltage sag and swell) and meet the EV user requirements [70]. These charging controllers will enable EVs' TCO to be further reduced whilst ensuring a satisfactory EV battery State of Health (SOH) and its durability.

6 Total Cost of Ownership (TCO) of EV/PHEV

Considering the increasing CO2 reduction legislation currently implemented in Europe and North America [68,71], there is an increasing demand for ULC 'green' cars [72,73], which include EVs and PHEVs. However, the market penetration of EVs is still well below the forecast figures as the global EV stock represents only 0.02% of all passenger cars [68] and their TCO remains high when compared with ICE based vehicles.

The financial drawback for EVs is constituted by the cost of the vehicle or its finance monthly payment, in addition to the battery lease monthly payment. This compound financial effect applies to all EVs available on the market today and it relates to the capacity of their traction battery.

In the following analysis, EVs are compared by considering their actual manufacturers' retail prices (ownership of vehicle and battery) whilst disregarding other relevant parameters such as the government subsidy or tax credit, vehicle standard equipment, technical refinement and brand name. The ratio of the vehicle cost to its maximum driving range is used to provide an indicative sense of the customer's EV value for money. According to Albert Lam, from Detroit Electric EV, batteries are responsible for about 54% of the production costs of an EV, 26% of the costs represent the drive system and the remaining 20% is the car body manufacturing [55].

Table 3. EVs retail cost/range ratio comparison [74,75]

Make	*Model*	*Retail Price*	*Market*	*Range*	*Cost/range ratio*
Nissan	***Leaf Visia 24 kWh***	£25,990	UK	124 mi	£209.6 per mi
Tesla	***Model S 60 kWh***	£54,900	UK	240 mi	£228.7 per mi

The most accessible Nissan Leaf model, called Visia and featuring a 24 kWh battery, is offered at £26 k in the UK, whereas the Tesla EV is sold at premium prices based on its large battery size. Considering the EV cost per mile it appears that there is a contained difference between the two vehicles examined, although their respective TCO is greatly affected by the initial retail price.

The same principle applies to PHEVs which are currently on the market.

Table 4. PHEVs retail cost/range ratio comparison [76,77,78]

Make	*Model*	*Retail Price*	*Market*	*(EV Range) Tot. range*	*Cost/ Tot range ratio*
Chevrolet	***Volt 16.5 kWh***	£35,255	UK	(50 mi) 300 mi	£117.5 per mi
Toyota	***Prius T3 4.4 kWh***	£21,064	UK	(15 mi) 540 mi	£ 39 per mi
Volvo	***V60 11.2 kWh***	£48,670	UK	(31 mi) 745 mi	£ 65.3 per mi

With the popular Toyota Prius very keenly priced, the Chevrolet Volt's TCO remains less favorable although it offers an extensive EV autonomy. The Volvo V-60 price bracket puts this executive PHEV and first diesel hybrid car in the world [79] in a different category altogether. The same can be said about its steep TCO. It can also be deduced that the Chevrolet Volt using a 16.5 kWh battery pack is about $5,000 more expensive than the Nissan Leaf, mostly due to its hybrid powertrain. In the case of the Toyota Prius costing below $30K it may seem that the sub $30K price bracket is necessary for those extended-range vehicles to go mainstream [80].

The current TCO trend has been challenged by Chevrolet as its latest offering for the new 2014 Spark EV 1LT on a low-mileage lease is significant since it offers the most affordable EV on the market for $199 per month for 36 months with an initial deposit of $999. This offers includes the full US federal tax credit which ranges from $0 to $7,500 [80]. In relation to the customer's TCO of an EV, it clearly appears that those vehicles with a limited range will be more appealing to the general public as their asking price will drop below $20K [80].

In order to further reduce TCO, a viable alternative is to charge EV users per usage, based on the common and well-established mobile phones business model. Considering the EV battery second life, a 5-year buy back guarantee with residual value would reduce the initial battery cost.

A study conducted by Roland Berger [81] forecasts that EVs' TCO may be competitive against ICEVs from the year 2015, based on a 3 year car lease with an annual mileage of 12k miles. The business model of leasing EV batteries is currently regarded as a means of reducing EVs' TCO for consumers as it offers an extended battery guarantee and reduced monthly costs.

7 EV/PHEV CO2 impact and production costs

When it comes to the production of vehicles, OEMs are committed to reducing CO2 emissions in innovative ways. Responsible and more sustainable ULCV manufacturing is applied in the Chevrolet Volt assembly plant as it employs 516 kW PV panels [82] to reduce its dependence on the power grid. These facilities reuse, recycle or convert to energy all waste created in their daily operations, which conserves resources. In addition, the Volt ICE, transmission and battery facilities are landfill-free.

The BMW's €400 million i factory drastically reinvents and simplifies car mass production and use of resources. The i3 city car features only 100 to 120 separate parts in its body structure, compared with about 400 parts in a typical steel body [83]. To paint its plastic body panels, BMW introduced a new type of paint shop, which produces no wastewater and has a fifth of the normal cost for a paint finishing facility for steel-bodied cars. As a result this factory uses about 70% less water and half the electricity [83] if compared with a common car plant.

The Mitsubishi Outlander PHEV uses green plastics, applied to high heat resistance areas, which are derived from the oils extracted from waste cashew nuts. This allows a reduction of CO2 emission by up to 12% compared to common petrol-based plastics [84]. The Outlander employs a high-capacity 12 kWh lithium-ion drive battery which enables an EV drive mode cruising range of over 55 km and an overall range in the region of 880Km [84]. Its CO2 emissions figure is as low as 44 g/km when the battery is fully charged, but it reaches up to 135g/Km when the battery is depleted [85]. These CO2 emissions confirm the fact that in most long journeys PHEVs are not necessarily cleaner than modern ICEVs [85].

A study by the Union of Concerned Scientists in the US comparing the global warming emissions from EVs with those from gasoline-powered vehicles and found that: nationwide, EVs charged from the electricity grid produce lower global warming emissions than the average compact gasoline-powered vehicle (with a fuel economy of 27 miles per gallon) - even when the electricity is produced primarily from coal in regions with the “dirtiest” electricity grids; in regions with the “cleanest” electricity grids, EVs produce lower global warming emissions than even the most fuel-efficient hybrids; and EVs charged entirely from renewable sources like wind and solar power produce virtually no global warming emissions [86].

Other authors comparing conventional and alternative vehicle option from an environmental and economic perspective argue that if electricity is generated from renewable sources, the electric car is advantageous to the hybrid vehicle; but if the electricity is generated from fossil fuels, the electric car remains competitive only if the electricity is generated onboard. Yet if the electricity is generated with an efficiency of 50-60% by a gas turbine engine connected to a high capacity battery and electric motor, the electric car is superior in many respects [88]. To charge EVs, studies indicate that the amount of generated CO2 emissions per kilometre is between 52-70g CO2/km [23].

Plug-in hybrid electric vehicles (PHEVs) consume both gasoline and grid electricity. The corresponding temporal energy consumption and emission trends are valuable to investigate in order to fully understand the environmental benefits. The 24-h energy consumption and emission profile depends on different vehicle designs, driving, and charging scenarios. Such a Californian scenario study assesses the potential energy impact of PHEVs by considering different charging scenarios defined by different charging power levels, locations, and charging time, with vehicle parameters based on realistic assumptions consistent with projected vehicle deployments. Results show that the reduction in petroleum consumption is significant compared to standard gasoline vehicles and the ability to operate on electricity alone is crucial to cold start emission reduction. The benefit of higher power charging on petroleum consumption is, however, small. Delayed and average charging are better than immediate charging for home, and non-home charging increases peak grid loads [88]. With rising fuel costs, EVs and PHEVs can be expected to deliver a certain level of financial benefit to consumers if seen on a longer time horizon of use, and depending on tax incentives and other public policy measures.

A Californian scenario study of charging demand shifts on an hourly basis for four different scenarios based on different electric circuit characteristics shows that circuit upgrades bring faster charging times, and reduce charging time differences between PHEV20 and PHEV60, with home charging replacing 40–50% of distances currently travel using ICEs with electric power for PHEV20 and 70–80% for PHEV60. If charging facilities are available in public parking facilities, which will lead to more daytime charging, PHEV20 can convert 60–70% of mileage from fuel to electricity, and 80–90% for PHEV60. Emission reductions will be higher than those percentages since PHEVs will cover a greater fraction when measured by the number of trips, which emphasizes the equivalent number of ICE starts. The study concludes that it is not certain that diverting charging demands to off-peak periods will maximize energy efficiency, since daytime charging will allow more trips by electricity, but will result correspondingly in higher peaks for high-demand-periods. There are limitations to the assessments provided by this study – and many others - as it does not fully account for environmental impacts from PHEV penetration. Specifically, increased emissions and other types of energy usage regarding extra grid electricity demand are not assessed [89].

8 EV/PHEV new business models and TCO reduction contributions across industries and regulatory context

Although the cost of a traction battery, at $1000 per kWh in 2008, has rapidly fallen to $485 per kWh in 2012 [68], it may take 3-4 years for these cost gains to benefit the auto industry and ultimately consumers.

The newly adopted business model by major EV makers to lease the battery separately from the vehicle is surely a necessary yet evolutionary step to reduce TCO considerably. In order to reduce EV production costs the following requirements should be observed:

- Creation of a standard type of battery cell which would increase manufacturing volumes and lower costs.
- Increase EV range by optimising aerodynamics, kerb weight, tyre rolling resistance and energy management.
- Redeploy used EV batteries for stationary application using light commercial load, residential load and for distributed generation technologies such as renewables, wind and solar.
- Without redeployment and V2G integration, partially or fully electrified powertrains are still at a significant cost disadvantage over the entire lifecycle compared to conventional powertrains, in terms of the total cost of ownership (TCO) if seen from both supply and demand perspectives. A revised public policy and regulatory landscape may be necessary to shift this, and there needs to be encouragement of battery-related research and investment.

OEMs currently experience a shortfall in profit margins if they sell a PHEV rather than a vehicle with a conventional powertrain. Customers benefits from lower energy costs due to lower fuel consumption, but OEMs are not fully recompensed for the extra cost it incurs.

KPMG’s 2013 Global Automotive Executive Survey hence suggests that 92% believe that consumers' number one criteria will be fuel efficiency, with 36% believing that plug-in hybrids will attract most consumer demand. 85% of surveyed executives think that downsizing ICE engines is the solution, with a higher proportion investing there, though with a sizeable chunk of OEMs investing in plug-in hybrids, yet with only 8% seeing battery technology as their biggest investment area [90]; something that needs to seen in context of the advantages and disadvantages of different battery technologies [91-94]. Energy efficient charging regimes of EVs will be important to electricity as fuel energy consumption [95].

9 Conclusions

According to the International Energy Agency (IEA), policy initiatives in 12 out of the 15 countries which are part of the IEA's Electric Vehicle Initiative (EVI), have been put in place to boost the introduction of sustainable transport through a range of EV financial support measures and other practical facilitations [68] to stimulate this market.

There are a number of key major conditions to be met to increase the uptake of PHEVs and EVs:

- A significant reduction in cost of Ion-Lithium battery and an increase in power density to provide EVs and PHEVs with an increased range. The IEA estimates that targeting a battery at $300 per kWh in 2020 [68] will make it competitive against an ICE.

- EVs and PHEVs price reduction through cheaper batteries and improved manufacturing processes will make EVs/PHEVs more competitive against ICEV. The IEA EV/PHEV Roadmap predicts that after 2015 the number of EVs/PHEVs will reach 7 million per year by 2020 [73]. If such a forecast is fairly reliable, manufacturing cost savings through larger volumes of production may be realized making these types of LCVs more appealing to own or lease.

- A broader development of national charging infrastructures through the widespread installation of public, commercial and private charging points. EVI countries are planning to install, as cumulative targets, about 2.4 million slow chargers and 6,000 fast chargers [68] by 2020.

- New business models applied to the use of EVs/PHEVs to lower customer's up front and monthly cost and to increase the availability of high power charging points in public and commercial environments. There is currently much uncertainty over the economics of rolling out and maintaining fast-charging infrastructure as investment is hardly profitable at low EV adoption rates, unless investment cost can be severely lowered. Besides competition with alternative charging solutions (home and work), the general EV adoption rate is detected as being a main risk factor for private investment in public charging infrastructure. If private investment takes place at this premature stage, it appears to be driven by other than project prospects: Charging stations may be used as a perk to attract consumers with main revenue generated from non-electricity sales, such as commodity sales or to a certain extent parking fees. Integrated organizational structures with electric utilities promise slight improvements in return on investment since additional profits on the electricity market side enter the investment calculus. These additional profits are, however, very low. Fleet operation and grid tariff exemption can significantly improve returns [96].

- Intelligent charging for different profiles of users, and perhaps even using day-ahead management systems instead of pre-set profiles have desirable consequences for the system (e.g. decrease in variable costs, reduction in carbon emissions, increase of reliability) for the grid system [97], it is therefore necessary to develop an "intelligent" charging strategy. Using an operation planning model, a study analyses the Spanish power system for 2020 under different EV penetration levels and charging strategies. The results show the benefits of using smart charging profiles instead of an unregulated profile, obtaining large cost reductions and maintaining system reliability levels [98].

Despite the technical and financial constraints for EV/PHEV adoption [99], it is worth noting that the latest EVs provide energy efficiency beyond 80%, as compared to ICEV (~30%) [68]. It remains clear that the toughest challenge to the large scale uptake of EVs/PHEVs in the forthcoming years is represented by the development of battery technology which can literally accelerate or stifle this evolution, with trade-offs between different battery technologies of the Lithium-ion family of battery technologies in terms of advantages and disadvantages in terms of safety, performance, specific energy, specific power, cost and lifespan. The second-life span and use of these batteries will be of significance and consequence also [100].

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