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A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles

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ABSTRACT

Electric vehicles have recently been gaining increasing worldwide interest as a promising potential long-term solution to sustainable personal mobility; in particular, battery electric vehicles (BEVs) offer zero tailpipe emissions. However, their true ability to contribute to greenhouse gas (GHG) emissions reductions can only be properly assessed by comparing a life cycle assessment of their GHG emissions with a similar assessment for conventional internal combustion vehicles (ICVs).

This paper presents an analysis for vehicles typically expected to be introduced in 2015 in two example markets (the UK and California), taking into account the impact of three important factors:

- Like-for-like vehicle comparison and effect of real-world driving conditions.
- Accounting for the GHG emissions associated with meeting the additional electricity demand for charging the batteries.
- GHG emissions associated with vehicle manufacture, disposal, etc.

This work demonstrates that all of these factors are important and emphasises that it is therefore crucial to clearly define the context when presenting conclusions about the relative GHG performance of BEVs and ICVs – such relative performance depends on a wide range of factors, including the marginal regional grid GHG intensity, vehicle size, driving pattern, loading, etc.

Definitions

Throughout this paper, the following definitions apply:

- Internal combustion vehicle (ICV) – the term ICV refers to a vehicle that employs only an internal combustion engine to meet its propulsion needs.
- Hybrid electric vehicle (HEV) – the term HEV refers to a vehicle that employs both an internal combustion engine and an electric drivetrain to meet its propulsion needs, but does not take electricity from the grid.
- Electric vehicle (EV) – the term EV refers to a vehicle that can draw part or all of its power from the electric grid.
- Battery electric vehicle (BEV) – the term BEV refers to a vehicle that draws all of its power from the electric grid, using only batteries for onboard energy storage.
- Plug-in hybrid electric vehicle (PHEV) – the term PHEV refers to a vehicle that draws part of its power from the electric grid via batteries, meeting the rest of its propulsion needs with an alternative energy source onboard (e.g., gasoline).
- Greenhouse gas (GHG) – a gas in the atmosphere that absorbs and emits radiation within the thermal infrared range, hence contributing to the greenhouse effect, and consequently global warming or climate change.
- Life cycle assessment (LCA) – an LCA considers the environmental impact (e.g., energy/material use and GHG emissions) of a product or service throughout its entire life cycle, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal.
- Fuel life cycle – this stage of the LCA, also known as Well-to-Wheels, covers the life cycle of the fuel (including its end use in the vehicle).
- Vehicle life cycle – this stage of the LCA covers the life cycle of the vehicle (excluding fuel use in its operation), i.e., the production of vehicle raw materials, the manufacturing and distribution of vehicle components and the whole assembly, the maintenance and repair of the vehicle throughout its life time, and the disposal of the whole vehicle.

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- Tank-to-Wheels (TtW) – the term TtW covers the vehicle in-use phase of the LCA.
- Well-to-Tank (WtT) – the term WtT covers the production and transport of fuel feedstock, and the production and distribution of finished fuels or electricity.
- Well-to-Wheels (WtW) – the term WtW is equivalent to fuel life cycle.

1. Background

Governments around the world are taking steps to address the challenges of sustainable mobility, energy security and climate change, most notably through measures aimed at addressing the greenhouse gas (GHG) emissions impact of the transportation sector. Transport currently accounts for around one quarter of global energy use and energy-related GHG emissions, with approximately three quarters of this from road transport (IEA, 2009). Demand for mobility is rising rapidly and vehicle numbers are projected to more than double before 2050 (Dargay et al., 2007; Meyer et al., 2007), with the highest growth rates in developing countries. In the absence of new policies, transport energy use and related GHG emissions are projected to increase by nearly 50% by 2030 and by more than 80% by 2050 (IEA, 2009). It has been proposed that reductions of 50% to 85% in global GHG emissions compared to 2000 levels will need to be achieved by 2050 to limit the long-term global mean temperature rise to within 2 °C (Forster et al., 2007). To meet the energy demand for transport, whilst at the same time reducing CO_2 emissions and improving air quality, will require integrated smarter mobility solutions that embrace a range of smarter vehicles and fuels, together with smarter infrastructure. In combination these help promote smarter usage. In this context Shell believes a mosaic of mobility options will be required for road transport, and is actively evaluating future energy supply for future drivetrains, as part of this integrated solution. Apart from the further development of today's gasoline and diesel engines powered by crude oil-based fuels and first generation and advanced biofuels, Shell also evaluates options from gas, in its different forms as compressed natural gas (CNG), liquefied natural gas (LNG) or gas-to-liquids (GTL), from hydrogen, and also from the energy required for electric vehicle mobility.

Electric vehicles (EVs) have been heralded as a promising potential long-term solutions to sustainable personal mobility. Battery electric vehicles (BEVs), in particular, offer zero 'Tank-to-Wheels' (TtW), i.e., tailpipe emissions, but their true ability to contribute to GHG emissions reductions can only be properly assessed by comparing a life cycle (i.e., cradle-to-grave) assessment (LCA) of their GHG emissions with a similar assessment for conventional internal combustion vehicles (ICVs). There can be no unique or definitive comparison between BEVs and ICVs, because life cycle GHG emissions depend on the defined boundaries of the system under consideration and the intrinsic assumptions in the calculations. Nonetheless, most analyses to date (e.g., CARB, 2009; Campbell et al., 2009) have shown significantly lower GHG emissions for BEVs based on the assumptions that they use electricity, which has a relatively low average grid carbon intensity, with high efficiency.

In this study, we have carried out an analysis for vehicles typical of those expected to be introduced in 2015, when fully developed BEVs are expected to become commercially available in significant numbers. The UK and California have been selected as example geographies for analysis due to availability of high quality electricity supply data and the genuine prospect of BEV introduction. Most importantly though, we have carried out the GHG LCA comparison taking into account together the impact of three important factors that have not been simultaneously accounted for in most previous analyses:

- Like-for-like vehicle comparison (BEV vs. ICV) including the effect of real-world driving conditions.
- Accounting for the GHG emissions associated with meeting the additional electricity demand for charging the batteries, rather than just assuming this can be described by the average carbon intensity of electricity generation.
- The GHG emissions associated with manufacture, maintenance/repair and disposal of the vehicle, also known as the vehicle life cycle.

Hybrid electric vehicles (HEVs) are also considered in this analysis but plug-in hybrid electric vehicles (PHEVs) have not been included because they introduce a high level of complexity and uncertainty due to the wide range of possible configurations and designs. The LCA energy consumption and GHG emissions of PHEVs should lie between those of HEVs and BEVs and could be evaluated by a similar analysis to that used in this study when valid vehicle data are available.

2. Key LCA factors

This section describes the three key factors that the authors believe need to be properly accounted for in any GHG LCA comparison between BEVs and ICVs, and the approaches that should therefore be adopted in such an analysis. For a brief literature review in this respect, as well as the detailed analysis and methodology adopted by this study, please refer to Appendix A.

The first factor considered was the need to conduct a true TtW comparison of (as close as possible) equivalent vehicles based on simulation of real-world driving. This requires comparisons to be made between matched vehicles in real driving conditions including similar vehicle loading and use of auxiliary systems such as heating or air conditioning. When making the comparisons it is appropriate to allow for further improvements in the efficiency of ICVs by 2015 and to include the expected reduction in CO_2 emissions from these vehicles resulting from mandated use of biofuels. By this time, we can also expect noticeable penetration of hybrid electric vehicles (HEVs, which are not electric vehicles but ICVs by our definition, because they do not take electricity from the grid), so a comparison with HEVs has also been carried out as an example of 'state-of-the-art' efficient ICVs. In the absence of fully developed BEVs and true performance data on future HEVs and ICVs, we have applied a rigorous and detailed modelling approach to assess the sensitivity to a range of vehicle classes, driving conditions and auxiliary loadings using modelling techniques and software widely employed in the automotive R&D community.

The second factor considered was the need to correctly assign the relevant GHG intensity to the electricity used to charge the batteries of the BEVs, i.e., the GHG emissions associated with the equivalent 'Well-to-Tank' (WtT) part of the BEV pathway. Most studies simply use average grid GHG intensity for the geographical region under consideration. There is growing acknowledgement amongst academics (Chen et al., 2008; Dotzauer, 2010; Elgowainy et al., 2009; Lambrecht and Pehnt, 2009; McCarthy and Yang, 2010; Hawkes, 2010) and some governments (DECC, 2010; Defra, 2008) that, for a true assessment of the overall CO_2 impact of the growth of electric vehicles, it is more relevant to consider the 'marginal' grid intensity than the average grid intensity. Marginal electricity is the incremental electricity that must be brought on stream to meet the additional demand from BEVs.

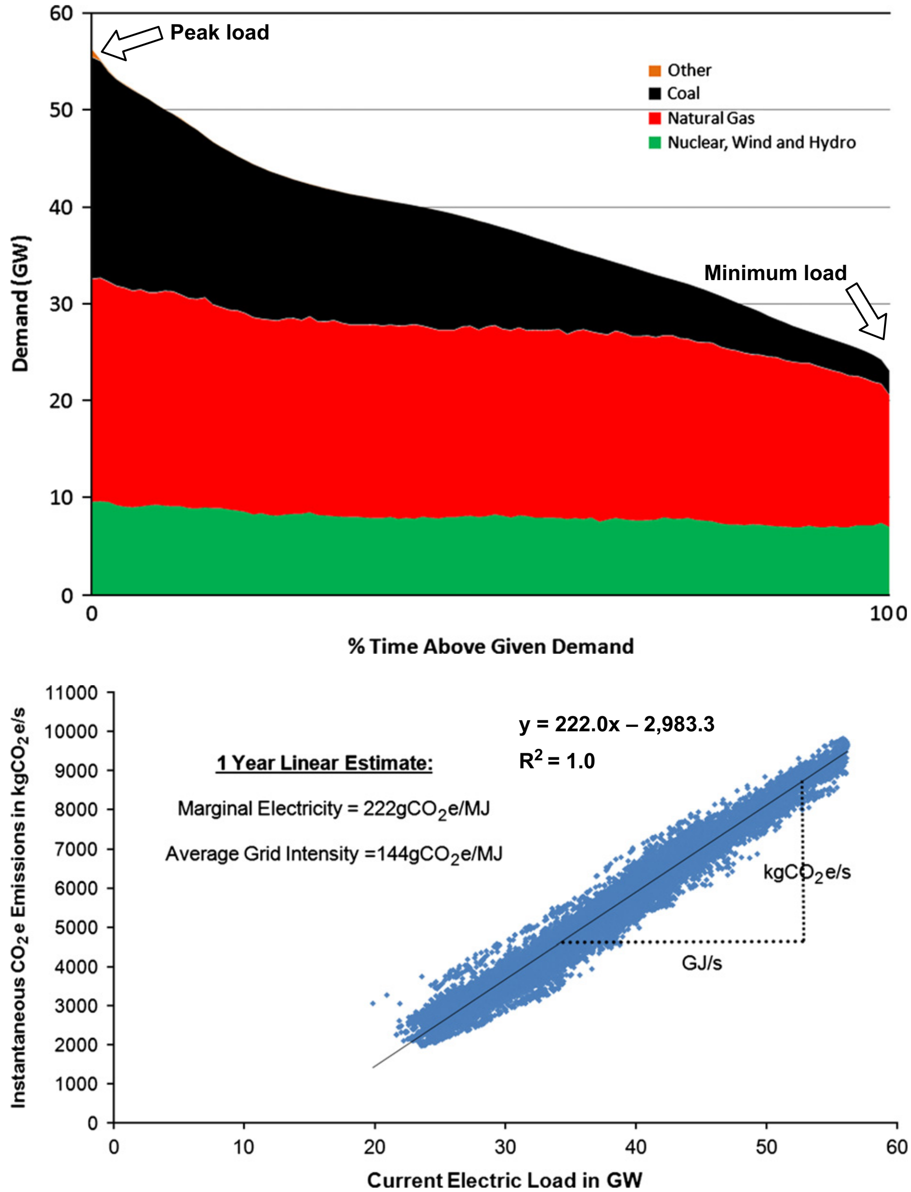


Fig. 1. Estimation of grid intensity in the UK: top – energy source mix for power generation as a function of demand; bottom – hourly electricity generation data from July 2009 to July 2010 (BM Reports, 2009) and the estimated real-time GHG emissions (authors' analysis).

In this context, it is important to note that low GHG intensity electricity such as nuclear or wind power is typically used to 100% of available production for various reasons, particularly the low short-run marginal costs. Wind, for example, cannot operate on the margin without some sort of storage system. Incremental demand is therefore typically met using fossil fuels[2]. This is shown in Fig. 1(top) for the UK: While the combined output of nuclear and wind power remains relatively stable, natural gas- and coal-fired power plants are used to meet incremental demand. Consequently the GHG intensity of marginal electricity is significantly higher than that of the grid average: An in-depth analysis of 2009–2010 hourly power generation data for the UK shown in Fig. 1(bottom) using typical GHG emissions values for the various energy sources (LBST E3 Database, 2011) suggests that the GHG intensity of marginal electricity is typically 60% higher than that of the grid average. Similarly, a recent study from the University of California Davies (McCarthy and Yang, 2010) suggests that it would be some 14–79% higher than that of the grid average in California, subject to large daily, seasonal and spatial variation as well as the actual load demand profile from electric vehicles. With a progressive shift from high GHG intensity, emissions intensive coal-fired power stations to cleaner, more efficient, lower GHG intensity gas-fired electricity generation, we can expect an overall reduction in GHG intensity. However, as these cleaner more efficient generation systems will inevitably be operated preferentially (for base load) to more costly low efficiency plants, marginal electricity will be dominated by the higher GHG intensity electricity and we can therefore expect that marginal electricity will continue to have higher intensity than the grid average for some time to come.

[2] One notable exception is pumped storage of hydro-power; however, because of its nature (limited and seasonal supply, low cost, etc.), hydro-power operating strategies (including pumped storage) tend to maximise total production over a long period. Although peak power demand can occasionally be met by pumped storage in a timescale of hours, this would not necessarily reduce the overall GHG emissions from the grid over a long period. Therefore, it is recommended that pumped storage be excluded from the definition of marginal electricity (Dotzauer, 2010).

Fig. 2 further illustrates the concept of marginal electricity and its implication in consequential LCA analysis of power demand scenarios – it is clear that, where low-GHG power sources are still well short of minimum demand, as they currently are in many countries, the GHG intensity of marginal electricity as a result of additional power demand from electric vehicles would be high. This will continue to be the case until low-GHG intensity generation capacity grows significantly to the point where it exceeds the (growing) minimum demand load. At this point some of the marginal demand for EVs will be met by low carbon intensity electricity and the life cycle emissions of EVs will start to reduce. The time when this point is reached is very uncertain and will vary considerably from region to region.

The third factor is the GHG emissions associated with the vehicle life cycle, which are not included in traditional 'Well-to-Wheels' (WtW) analyses such as Elgowainy et al., 2009. Although these emissions typically account for a significant proportion of the overall life cycle emissions associated with a light-duty vehicle, this factor is not normally considered when comparing different fuel pathways in traditional ICVs because there is no significant difference between the vehicle life cycle emissions associated with a gasoline-, diesel- or natural-gas fuelled vehicle. However, BEVs utilise considerable quantities of batteries and battery manufacture tends to be energy and GHG emissions intensive. There are limited data available on which to base a rigorous analysis, but using a series of reasonable approximations we have shown that this can make a considerable contribution to the difference in overall life cycle emissions between BEVs and ICVs.

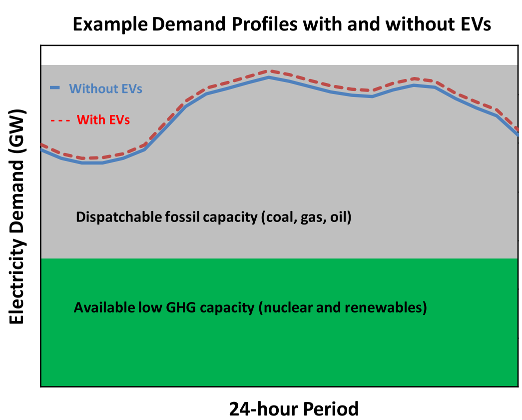


Fig. 2. Example power demand scenarios with/without EVs.

3. Results and discussion

Mathematical models (see Appendix A for more detail about the models, and assumptions made in the analysis) were used to explore the effect of various factors on the comparative GHG emissions between 2015 ICVs, HEVs and BEVs on a g CO_2eq/km basis, and some examples of the results are shown in Figs. 3 and 4. For each vehicle in each geographical region, eight driving patterns are investigated in total, namely:

- Two vehicle speed profiles, based on drive cycles used for vehicle certification.
- Two vehicle loading cases, i.e., driver with/without additional passenger(s)/cargo.
- Two accessory use cases, i.e., no accessory (air conditioning, etc.) vs. typical accessory use.

These combinations cover a broad spectrum of typical real-world driving conditions, respective of the two regions. For simplicity, two cases are presented and discussed in detail in this paper, where the BEVs show the lowest and highest absolute energy efficiency within the investigated space of driving conditions; however, note that even the 'lowest efficiency' case is considered representative of day-to-day vehicle use.

For a mid-size passenger vehicle in the UK under urban driving conditions with low passenger and accessory loading (Fig. 3, left), the BEV has lower WtW and overall life cycle (fuel and vehicle) GHG emissions than the ICV. The basis on which the GHG intensity of the electricity is assigned makes a very significant difference. Where marginal grid intensity is used, the overall life cycle emissions of the BEV are almost identical to those of an equivalent HEV for this set of conditions. The differences in vehicle life cycle emissions are smaller than the differences in the WtT part but still significant – these are primarily due to BEVs having higher vehicle weights and EV battery having a higher GHG intensity – the vehicle life cycle emissions of the BEV being around 16 g CO_2eq/km higher than an ICV (i.e., of the order of 10% of overall life cycle emissions). For the BEV, the vehicle life cycle emissions represent 30–50% of the total life cycle GHG emissions.

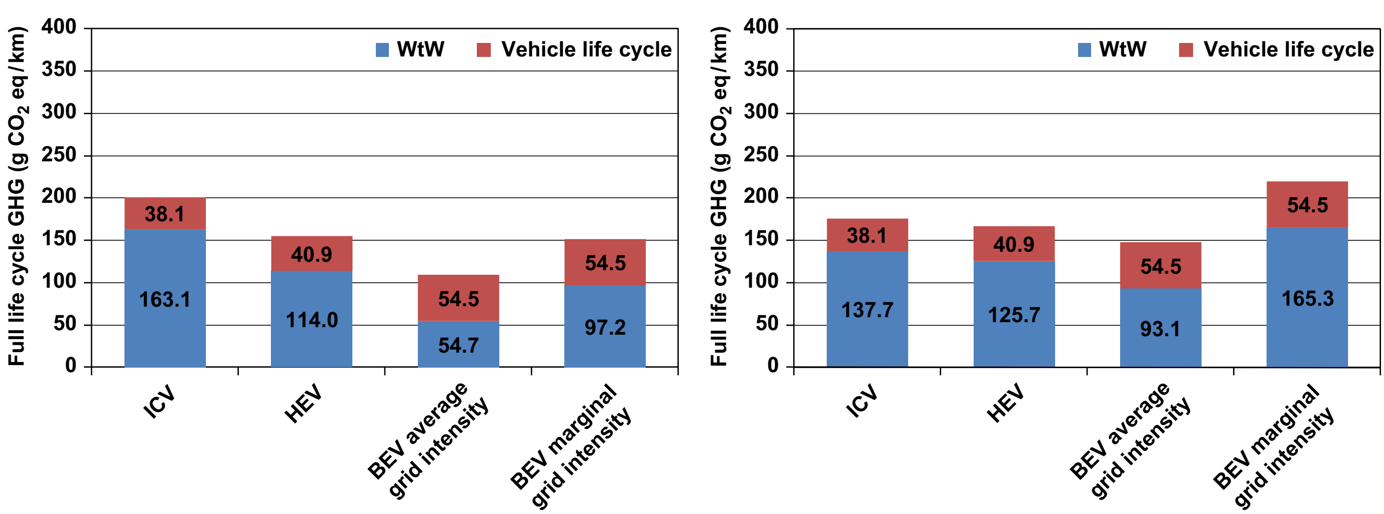
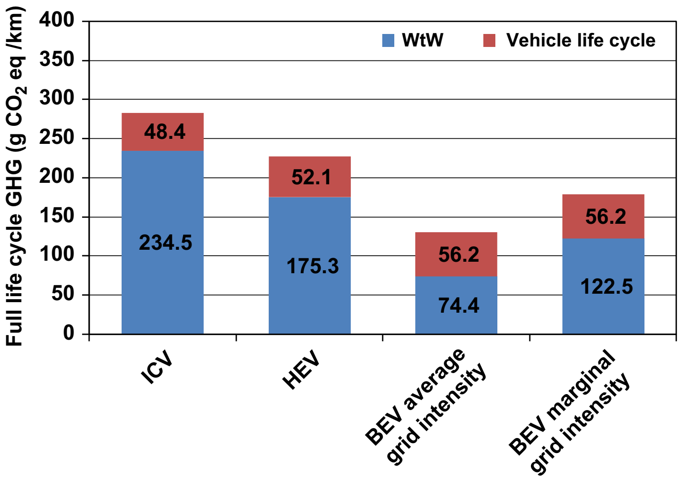


Fig. 3. Comparison of the WtW and vehicle life cycle emissions from matched mid-size ICV, HEV and BEV in the UK in 2015 (15-year vehicle life time, 12,000 km/year): left – lower speed and load (urban, driver only, no accessory) driving conditions; right – higher speed and load (extra-urban, driver+loading, accessory) driving conditions.



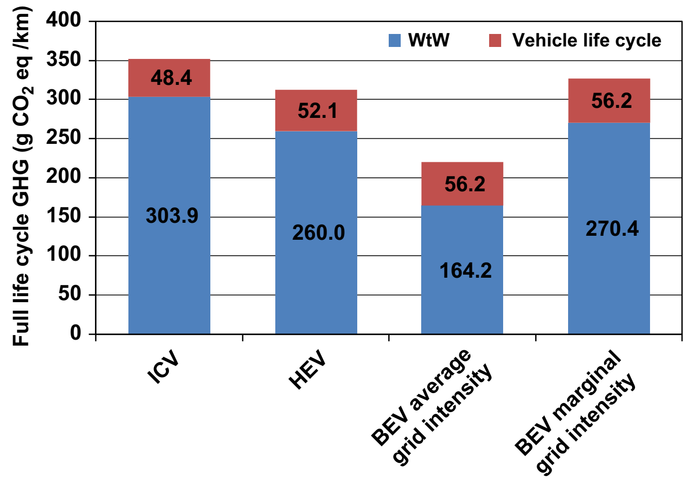


Fig. 4. Comparison of the WtW and Vehicle life cycle emissions from matched SUV-class ICV, HEV and BEV in California in 2015 (15-year vehicle life time, 19,300 km/year): left – lower speed and load (urban, driver only, no accessory) driving conditions; right – higher speed and load (extra-urban, driver+loading, accessory) driving conditions. **NOTE** – the methodologies adopted in this work can be readily applied to plug-in hybrid electric vehicles (PHEVs), and their results will most likely fall between those of HEVs and BEVs, on a like-for-like basis, primarily because:

- The TtW energy use and GHG emissions of PHEVs will fall between those of HEVs and BEVs.
- The vehicle life cycle GHG emissions of PHEVs will also likely fall between those of HEVs and BEVs, because one of the most sensitive factors influencing the vehicle life cycle is the batteries employed by HEVs/PHEVs/BEVs and the batteries of PHEVs have properties in between those of HEVs and BEVs (Kalhammer et al., 2007; Bradley and Frank, 2007).

For higher speed and load driving, the overall efficiency of ICVs increases while that of BEVs decreases. For the higher speed and higher vehicle and auxiliary loading case (Fig. 3, right), this results in a deterioration in performance of the BEV such that, when marginal electricity is considered, both its WtW emissions and overall life cycle emissions become greater than those of the HEV and the ICV. Even in the case where average grid intensity is assumed, the GHG emissions of the BEV are only slightly better than those of the ICV and HEV.

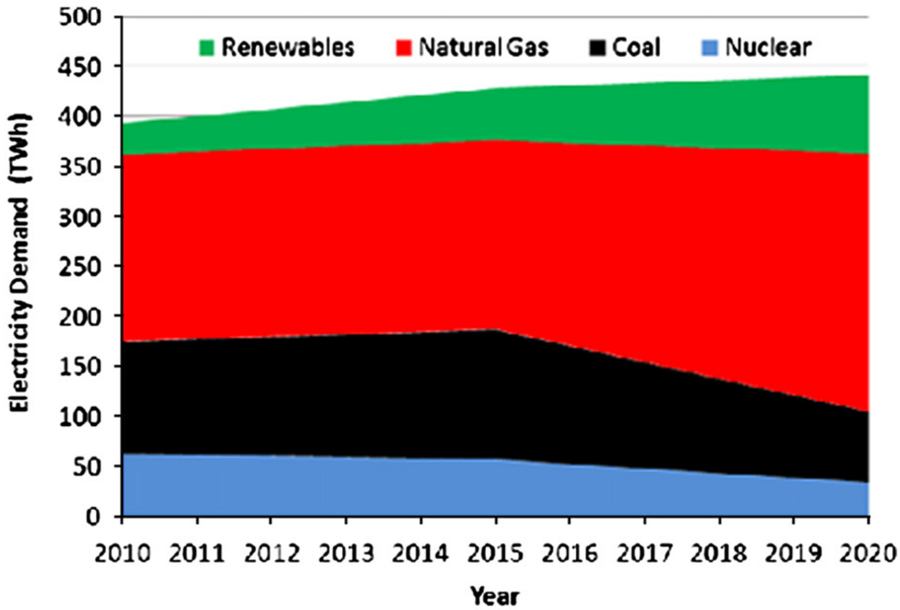
For the case of a sport utility vehicle (SUV) in California (Fig. 4), the WtW GHG emissions per km driven are higher than those in the UK mid-size vehicle case. The differences in vehicle life cycle emissions between the vehicle classes are smaller and their relative importance to the overall life cycle emissions becomes diminished because the higher WtW GHG emissions are a bigger fraction of the overall life cycle emissions. In this case, the BEV always has lower emissions than the ICV, although again the assumption about the intensity of the grid electricity production is a critical factor in the size of this difference. As in the case of the smaller vehicle in the UK, vehicle and accessory loading and speed have a significant influence (over a factor of two) on the BEV's WtW GHG emissions.

However, due to the highly variable design features of PHEVs and the absence of a good match among ICV/PHEV vehicle models, this work does not explicitly consider PHEVs.

As with all life cycle analyses, these results are sensitive to a range of different underlying assumptions (see Appendix A for some discussion on parameter sensitivities). Therefore, they should be taken as indicative rather than absolute. They demonstrate that BEVs can have lower LCA GHG emissions than ICVs in some scenarios but they also show how important it is to consider a wide range of contributory factors when assessing the GHG emissions impact in a specific set of circumstances. The assumptions used in this study are those that we currently believe best provide a fair and accurate comparison between near-future BEV and ICV technologies, but alternative assumptions or scenarios could be equally valid. Nonetheless, we believe that the direction and the approximate scale of effects investigated are well represented by the results from this study.

The results presented here do not undermine the long-term potential of BEVs to give extremely low life cycle GHG emissions if the grid can be decarbonised to the point where marginal electricity has low GHG intensity. They do however challenge the widely held belief that BEVs can provide a significant contribution to GHG reduction from personal transport in the short to medium-term. Fossil fuels will continue to dominate power generation in many markets up to 2020, providing more than 60% of the generated electricity (International Energy Outlook, 2010) – see Fig. 5 (top) for an example of projected electricity generation in the UK towards 2020. This is particularly relevant for markets in which nuclear power is being phased out. In such cases, marginal electricity will continue to be generated using a mix of fossil fuels (natural gas, oil and coal) depending on the regional merit order. It is worth noting that there may be some exceptions to this trend where decarbonisation of the electric grid could happen faster than, e.g., in the UK case: (Fig. 5 (bottom)), the U.S. Department of Energy (DOE) predicts a 52% share of renewables and only a 31% share of fossil fuels in the electricity generation mix in California by 2020 (Annual Energy Outlook, 2010). However, even in such a case, marginal electricity is still likely to be generated from mostly fossil fuels, as is currently the case. This is because most of the renewable electricity will be from wind and conventional hydropower, but neither wind nor hydropower is likely to feed marginal electricity demand due to the intermittent nature of wind power and the typically low short-run marginal costs associated with conventional hydropower. Therefore, the authors believe that the results presented here could well be valid out to at least 2020. In this period, further increases in the mandated use of sustainable, low carbon footprint biofuels and progressive engine and vehicle efficiency improvements could further improve the relative position of ICVs and HEVs compared to BEVs, the latter being likely to improve in cost, range and operability more than in efficiency.

Finally, it is important to be clear that, whilst there is a strong case for considering marginal electricity supply, it is very likely that, once established in the market, any attribution of GHG emissions to electric vehicles will be undertaken within a regulatory framework that uses the grid average intensity.



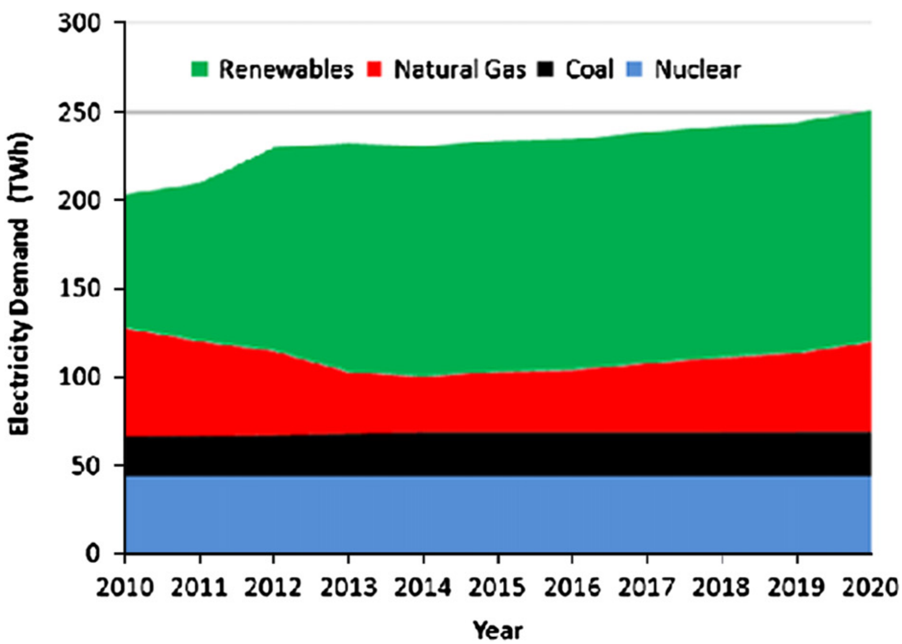


Fig. 5. Future grid mix towards 2020: top – predicted electricity consumption and generation in the UK (Wood Mackenzie, 2009); bottom – Department of Energy (DOE) projection of electricity production from primary fuels in California excluding imports (Annual Energy Outlook, 2010).

4. Conclusions

Based on life cycle analyses of GHG emissions from matched ICVs, HEVs and BEVs that are representative of those expected to be available in the market in 2015 in the UK and California, we conclude that:

- BEVs can deliver significant GHG savings compared to ICVs providing that the grid GHG intensity used to charge the batteries is sufficiently low.
- BEVs perform best relative to ICVs (in terms of GHG emissions) in low speed (e.g., urban) driving and when lightly loaded with weight and auxiliaries.
- Vehicle life cycle emissions (associated with vehicle manufacture and disposal etc.) are higher for BEVs than ICVs due to the GHG emissions associated with battery manufacture. In some circumstances the vehicle life cycle emissions can constitute a significant part of the overall emissions associated with BEVs.
- Marginal grid GHG intensity gives a more realisitic measure of the GHG impact of the growth of electric vehicles than does average grid GHG intensity. Marginal electricity is generally produced from fossil fuels resulting in significantly higher GHG intensity and hence higher life cycle GHG emissions from BEVs.
- In the UK context, using the marginal grid intensity indicates that a mid-size BEV operated under higher speed and load conditions can have significantly higher WtW and overall life cycle emissions than comparable ICVs. Under lower speed and load conditions, the BEV emissions are similar to those of a matched HEV and lower than a matched ICV.
- In the California context, an SUV-class BEV is found to have lower overall life cycle GHG emissions than a comparable ICV. However, the gap is significantly reduced in high load/speed

scenario. The effects of marginal electricity, vehicle speed and load and inclusion of vehicle life cycle emissions on the differences between BEVs and ICVs are all directionally similar to those in the UK context.

- It is important to reference to the context when presenting general conclusions about the relative GHG performance of BEVs, HEVs and ICVs. The relative performance depends on a wide range of factors, including the relevant grid GHG intensity, vehicle size, driving pattern, loading etc., and any meaningful comparison that is used to inform policy making should take these fully into account for the specific situation being considered.

In summary, we have shown how each of the three important LCA factors can influence the overall life cycle GHG emissions of three vehicle types from four distinctive segments; however, further understanding and research is still required to better assess their relative merits, in the context of energy use and GHG emissions by the transport sector. First of all, as soon as a significant number of electric vehicles become commercially available, their real-world performance (e.g., practical energy efficiency) and consumers' experience with them (usage pattern etc.) will need to be investigated, and compared with other drivetrain options on a like-for-like basis. Secondly, detailed analysis of marginal electricity should be conducted for key potential EV markets, e.g., to inform policy making regarding electric mobility. Finally, up-to-date, primary and detailed vehicle life cycle inventory analysis will also be useful when studying a vehicle's true ability to contribute to GHG emissions reductions.

Appendix A. Life cycle assessment

This appendix first gives a brief summary on key issues identified by the authors from a comprehensive literature review. The ensuing sections then detail the goal and scope definition, modelling approaches, and key assumptions used in this life cycle GHG assessment between BEVs, HEVs and ICVs.

A.1. Literature review

The R&D community of advanced automotive fuel/propulsion technologies are increasingly aware of the importance of life cycle assessment – this has been demonstrated by numerous publications in the past decade. In addition to their different goal and scope definitions, these studies employ a broad range of assumptions and methodologies, sometimes resulting in disparate or even contradictory conclusions. This subsection briefly critiques the approaches and assumptions of individual studies, and discusses the potential sources of uncertainty and reasons for the variations observed in the literature.

The first important issue we identified from the literature review is with regards to an LCA's scope. When investigating the life cycle sustainability impacts of automotive fuel/propulsion technologies, a large portion of the literature to date applies the Well-to-Wheels (WtW) approach (Elgowainy et al., 2009; Bradley and Frank, 2007), i.e., the analysis typically only considers the fuel life cycle (covering the feedstock production and transport, as well as fuel production, distribution and use), whilst omitting the vehicle life cycle (the manufacturing, distribution, maintenance and disposal of raw material, components and whole vehicle assembly).[3] However, in some cases of advanced propulsion technologies, such as the BEV which employs a large amount of electric components, the vehicle life cycle could make a greater contribution to the whole life cycle energy consumption and GHG emissions than that of conventional technologies (BERR and DfT, 2008). Furthermore, with rising vehicle energy efficiency and the extra energy input for producing lighter weight and energy-intensive materials, the contribution from the vehicle life cycle becomes increasingly important, in some cases exceeding that from fuel processing and distribution (Schafer et al., 2006). Studies (e.g., Demel, 2009; Zamel and Li, 2006a) have also shown that the increased use of recycled materials can mitigate the energy consumption and GHG penalty introduced by energy-intensive materials to the vehicle life cycle. In general, the literature (e.g., Lane, 2006; Zamel and Li, 2006a) suggests that the contributions to total life cycle energy consumption and GHG emissions from the fuel life cycle (excluding fuel use) and the vehicle life cycle are of similar order of magnitude. In addition, many studies (e.g., Lane, 2006; Zamel and Li, 2006a, 2006b) tend to focus on the impact of energy-saving and emissions reduction technologies based on a single vehicle model/segment, whilst a fleet-based analysis (Schafer et al., 2006; Bandivadekar et al., 2008; Ma et al., 2011) is essential in assessing which technologies to invest in, at what points in time, and to what extent in order to achieve substantial reductions in energy consumption and emissions.

A variety of WtW figures have been reported in the literature, ranging from 30% to 65% for GHG emissions reduction benefits of PHEVs, BEVs and FCVs compared with conventional gasoline vehicles under standard test cycles (laboratory-measured or computer-modelled). For instance, A WtW simulation study (Elgowainy et al., 2009) demonstrated great CO_2 reduction potential of PHEVs particularly using bio-fuels; in addition, with biomass-based fuels, regular HEVs may realise more GHG emissions benefits than PHEVs if the marginal generation mix is dominated by fossil sources. However, such studies employed diverse assumptions, methodologies and baseline vehicles, sometimes resulting in 'unfair' comparisons – for example, one researcher (Randall, 2009) compared the Tesla (a sports BEV) with the 2006 average UK registered gasoline and diesel cars, confusing not only the different vehicle segments but also the age of the technologies.

Second, the real-world performance and impact of electric vehicles are dependent on the conditions of use of the vehicle, although the vast majority of the existing literature has focused on vehicle-certification type test cycles. Each study would make its own set of assumptions regarding vehicle configurations, drive cycle/driving and charging behaviour, characteristics of energy sources etc., to predict real-world energy consumption and to allow for comparisons with conventional vehicles. Therefore, it is important to recognise some of the distinctions between ways of obtaining the results from laboratory testing, simulation, Original Equipment Manufacturer (OEM) certification and real-world driving experience. It should also be noted that differences in energy consumption, emissions and performance between a vehicle pair to be compared are not always attributable solely to hybridisation/electrification.

Finally, the total real-time electricity generation for charging electric vehicles features a dynamic mix of various electricity pathways, which results in an average GHG emissions intensity specific to the corresponding electric grid mix, at a specific time of the day, in a specific day of the year and within a specific region where the electricity is generated, dispatched and consumed. The majority of studies to date, including the one prepared for the

[3] Comprehensive life cycle inventory (LCI) models, e.g., LEM by Delucchi (2003) and GREET by Wang (Burnham et al., 2006; Wang, 1999) have also been developed and widely used to analyse automotive fuel and vehicle life cycles; however, to the authors' best knowledge, these have not been adopted to simultaneously address the three key LCA issues highlighted in this paper.

California Low Carbon Fuel Standard (LCFS) (CARB, 2009), focus on the annual average grid mix of a certain geographical region; however, others (e.g., McCarthy and Yang, 2010; Dotzauer, 2010) argue that, when deciding on a policy aimed at promoting electric mobility to reduce GHG emissions, a marginal approach is more appropriate. This approach tracks the temporal and spatial demand/supply situation to determine what energy source is actually feeding the electricity generation at the very point when and where the BEVs are charged. The marginal approach is required to answer questions such as: What is the impact on total GHG emissions of an increased demand in electricity to power BEVs? It is a necessary component in a specific type of LCA named consequential LCA (as opposed to the other type, attributional LCA).

In summary, the observed highly variable results reported by various studies in the literature can be attributed primarily to the particular set of assumptions and simplifications that each study makes, with respect to the following:

- Timeframe, geographical area and types and attributes of fuel/propulsion systems studied.
- Boundary conditions and LCI accounting methods (process-based vs. economic input–output).
- Process models for various stages of the fuel and vehicle life cycles, e.g., marginal vs. average grid intensity.
- Characteristics of feedstock, processed fuels and electricity
- Technological and commercial evolution of fuel/propulsion technologies.
- Comparison criteria for alternatives vs. baselines.
- Fuel/vehicle usage pattern and functional unit.
- Referencing and adjustment to data and results from other studies and sources.
- Ways of handling uncertainty.

This paper aims to contribute to advancing the understanding of the simultaneous effects of many of these issues in the fair comparison of fundamentally different mobility pathways – its goal and scope are defined in detail in the next subsection.

A.2. Goal and scope definition

The scope of this analysis covers the whole life cycle, including the following phases:

- Fuel life cycle
  - The production and transport of feedstock.
  - The production and distribution of fuels and electricity.
  - The vehicle in-use phase (also known as Tank-to-Wheels).
- Vehicle life cycle
  - The production of raw materials.
  - The manufacturing and distribution of vehicle components and the whole assembly.
  - The maintenance and repair of the vehicle throughout its life time.
  - The disposal of the whole vehicle, also known as the vehicle end-of-life (VEOL) phase.

The vehicle technologies considered in this work are:

- Spark ignition ICV (gasoline).
- Compression ignition ICV (diesel).
- BEV utilising electricity from a variety of energy sources and pathways.

Four vehicle pairs are selected for this study, representing four distinctive vehicle segments, where BEVs are compared with baseline ICVs (either gasoline or diesel):

- Super-mini passenger car – the Daimler SmartForTwo gasoline ICV vs. 2nd generation Smart BEV.
- Mid-size passenger car[4] – the BMW Mini Cooper S gasoline ICV vs. Cooper E BEV.
- Sport utility vehicle (SUV) – the Porsche Cayenne gasoline ICV vs. Phoenix SUV BEV.
- Light goods vehicle (LGV) – the Ford Transit Connect diesel ICV vs. Ford/Smith Ampere BEV.

The timeframe is set to be 2015+, when the selected BEVs are expected to be commercially available on the EU and U.S. market. Detailed vehicle specifications can be found in Tables A1 and A2. For each segment, a notional, full HEV is also analysed, although such vehicles may not actually be produced in reality.

The GHGs included in the study and their global warming potential (GWP) are as follows (Forster et al., 2007; Weckert, 2008):

- Carbon dioxide (CO_2), GWP=1.
- Methane (CH_4), GWP=25.
- Nitrous oxide (N_2O), GWP=298.
- Refrigerant for vehicle air conditioning (A/C), which may be one of the following:
  - Hydrofluorocarbon HFC-134a ($C_2H_2F_4$), GWP=1430.
  - Hydrofluorocarbon HFC-152a ($C_2H_4F_2$), GWP=124.
  - Propane (C_3H_8), GWP=3.
  - Carbon dioxide (CO_2), GWP=1.

Since the majority of the vehicles on the road in the timeframe of 2015+ will have air conditioning, e.g., up to 95% of all passenger cars (Weckert, 2008), and the primary refrigerants to be used will still be HFC-based, emissions from them are considered significant in this work and hence included.

The following aspects of the life cycle are **not** included in the system boundary, either due to the potential complexity/insignificance, or lack of necessary data/information:

- Non-CO_2 GHG emissions (unburnt hydrocarbons, NO_x, etc.) from the tailpipe.
- Energy use and emissions involved in building and dismantling, e.g., the tools, refineries, factories and plants that facilitate, e.g., the production of raw materials and vehicles and their end-of-life treatment.
- Energy use and emissions involved in building the infrastructure (e.g., roads, filling stations for ICVs or charging stations for BEVs, etc.).
- An unknown part of the supply chain in the vehicle life cycle, e.g., tier-1, 2, 3… suppliers, maintenance, servicing and repair etc. although some of the data quoted from the literature may have considered certain aspects of these.
- Research, development and administrative activities.

A.3. Function and functional unit

The primary function of the system analysed here is for a vehicle to carry a certain load, passengers and/or cargo, throughout its life

[4] The definition of this vehicle segment reflects the current situation in Europe, covering passenger vehicles with a typical weight of c.a. 1200 kg, 4/5 seats and a propulsion performance similar to that currently provided by a 1.6 L PFI gasoline IC engine. However, note that this segmentation is rather arbitrary; it may not be applicable to other geographical locations, e.g., North America, and is likely to change over time.

Table A1
ICV specifications.

Vehicles	SmartForTwo Gasoline ICV	Mini Cooper S Gasoline ICV	Porsche Cayenne Gasoline ICV	Transit Connect Diesel ICV
Model year	2015+	2015+	2015+	2015+
Powertrain	Turbo PFI S2	Turbo DISI S3	Turbo DISI S4	Duratorq TDCi S3
Capacity (L)	0.465	1.199	1.984	1.315
$BMEP_{max}$ (bar)	25	30	25	25
$Power_{max}$ (kW)	40	120	200	80
Compression ratio	9.0	10.5	10.5	18.5
Stroke (m)	0.067	0.0858	0.0928	0.082
Valves per cylinder	2	4	4	4
Diesel particulate filter	–	–	–	Yes
Stop/start	Yes	Yes	Yes	Yes
Vehicle				
Kerb weight (kg)	800	1130	1930	1360
Aerodynamic drag	0.340	0.330	0.320	0.35[a]
Frontal area (m^2)	1.93	1.99	2.78	2.60[a]
1st order rolling resistance	0.007	0.007	0.007	0.007
1st gear ratio	3.380	3.310	4.680	3.667
2nd gear ratio	2.450	2.130	2.530	2.048
3rd gear ratio	1.760	1.480	1.690	1.258
4th gear ratio	3.380	1.140	1.220	0.921
5th gear ratio	2.450	0.950	1.000	0.705
6th gear ratio	1.760	0.820	0.840	–
Final drive ratio	3.920/1.551	3.650	3.700	4.060
Wheel rolling radius (m)	0.292	0.310	0.368	0.317
Payload (kg)	–	370	785	898
Vehicle accessory load (W)	0	100	500	200

[a] Data not available, derived from similar vehicles.

Table A2
BEV specifications.

Vehicles	Smart EV	Mini Cooper E	Phoenix SUV BEV	Ford/Smith Van BEV
Model year	2015+	2015+	2015+	2015+
Powertrain				
Motor $Power_{max}$ (kW)	30	150	110	50
Motor $Torque_{max}$ (N$*$m)	–	220	500	–
Battery type	Li-ion	Li-ion	Li-ion	Li-ion
Battery capacity (kWh)	–	35	35	24
Battery cycle life	up to 400,000 km	–	up to 500,000 km	–
Range (km)	–	160+ (city)	160+ (city and highway)	160+
Vehicle				
Kerb weight (kg)	929	1465	2,186	1520
Aerodynamic drag	0.340	0.330	0.320[a]	0.35[a]
Frontal area (m^2)	1.93	1.99	2.78[a]	2.60[a]
1st order rolling resistance	0.007	0.007	0.007	0.007
Wheel rolling radius (m)	0.292	0.310	0.368[a]	0.317
Energy use (kWh/km)	–	0.14 (city)	–	–
Payload (kg)	–	195	318	800

[a] Data not available, derived from similar vehicles.

time, which is assumed to be 15 years. The functional unit used in this report is therefore per vehicle kilometre travelled, which depends on the geographical region where the vehicle is used, e.g., assumed to be 12,000 km/year for the EU (European Road Statistics, 2009) and 12,000 miles/year for the U.S. (National Transportation Statistics, 2009).

A.4. Methodology

The methodology used in the LCA is chosen primarily considering availability of data/information for the 2015+ vehicles to be studied. An overview of the methodology used for each phase of the LCA is given in this subsection.

A.4.1. Energy sources

This phase is often referred to as the Well-to-Tank (WtT) part in the fuel life cycle.

A.4.1.1. Electricity. The methodology used for estimating the WtT GHG emissions associated with electricity is based on standard LCA guidelines on this topic and power generation databases in the EU and U.S. context (API, 2007; API Compendium, 2009; UCTE, 2008, 2009a, 2009b; EPA e-GRID, 2007; JRC/EUCAR/CONCAWE, 2008).

Fig. A1 shows some typical values including transmission losses in the European context, calculated using the E3 database software (LBST E3 Database, 2011). It can be seen that these values agree well with industry guidelines on GHG emissions accounting for power generation.

A typical LCA of BEVs would attempt to compare them with their conventional counterparts and estimate their potential energy and GHG emissions saving. It is the authors' view that the marginal approach should be used wherever possible, especially when estimating the **potential** GHG consequences of policies intended to promote the uptake of BEVs. Unfortunately, obtaining sufficient data to determine the marginal grid intensity for a wide range of relevant geographical regions has proven extremely challenging, partly due to the complex and dynamic nature of such an analysis and partly because such information is often treated as confidential by involved parties. It is even more challenging to analyse marginal electricity for the future, where there would be large uncertainties in both the technological and economic considerations, such as the short-run marginal cost, ramp rate limits, start-up cost, regional transmission, availability of renewable energy sources, CO_2 trading schemes and price etc. Nevertheless, this LCA acknowledges that a choice between the two approaches, 'average' vs. 'marginal', should be based on the actual application and the goal and scope definition of the LCA.

Table A3 lists the grid GHG emissions intensities in different regions used in the LCA (average grid intensities are given for reference only). The estimate for the UK grid average takes into account potential grid decarbonisation between now and 2015.

Note that there would be substantial uncertainty in estimating marginal electricity for the future and no drastic infrastructure change are planned by the UK and California authorities, the 2015+ marginal grid GHG intensities for these two regions were assumed to be the same as the current ones. Additionally, since there is only an insignificant amount of BEVs in use at the moment and the market penetration of BEVs is expected to occur in an incremental manner rather than an immediate step change, the current estimates of marginal grid are considered valid between now and 2015.

It can be seen in Table A3 that the marginal grid intensity can be considerably higher than the grid average, with the difference depending on how the marginal electricity is generated. In the UK case, marginal electricity is largely generated using coal and only a small fraction of natural gas, whilst in California marginal electricity is generated using predominantly natural gas. The GHG intensity of marginal electricity in other regions will vary between these two extremes, i.e., generated using a mix of natural gas, coal and other fossil fuels. The California case is not typical for the rest of U.S., but it is a significant economy and market on its own and so warrants being considered separately.

It should be noted that the development and adoption of smart grid technologies may help improve grid operations and establish synergies between the grid and EVs, and ultimately result in additional GHG emissions reduction for both the grid and EVs. However, the authors believe that the build-up of a universal smart grid infrastructure will take considerable time, and therefore exclude its impact from the scope of this paper. Further research is recommended in this respect.

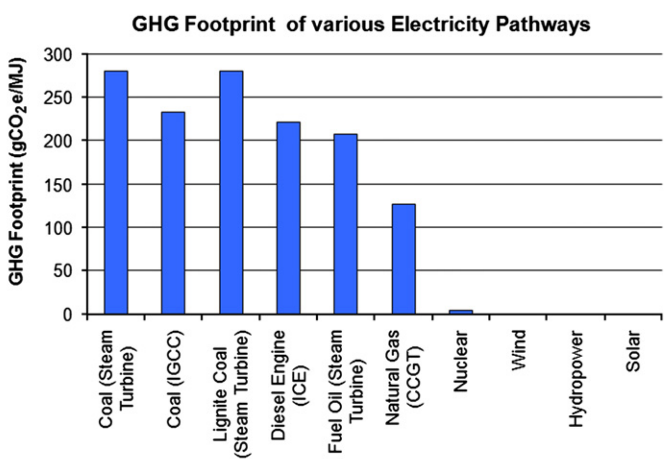


Fig. A1. GHG emissions intensity of different feedstocks/technologies for electricity generation.

Table A3
Grid GHG emissions intensities in different regions in the 2015+ timeframe.

	UK average	UK marginal	California average	California marginal
Electricity ($g\ CO_2eq/MJ$)	125.0[a]	222.0[a]	105.4[a,b]	173.6[a,b,c,d]

[a] Authors' analysis.
[b] The LCFS (CARB, 2009) gives a near-term average grid intensity of 124.1 g CO_2eq/MJ, however, our analysis show that California has the potential to decarbonise its grid considerably in the next decade primarily due to growth in renewable electricity generation.
[c] The LCFS gives a near-term marginal grid intensity of 104.7 g CO_2eq/MJ, however, our analysis and McCarthy and Yang (2010) both show that this number may not be representative.
[d] McCarthy and Yang (2010) estimated the marginal grid GHG intensity in California to vary from 137 g CO_2eq/MJ to 215 g CO_2eq/MJ, with an annual demand-weighted average of 174 g CO_2eq/MJ. According to their analysis, the instantaneous marginal intensities tend to be lower at night than in the middle of the day, and lower in winter than in summer. Therefore if the instantaneous marginal intensity were to be applied to BEV LCA calculations, the results would show large daily and seasonal variations.

A.4.1.2. ICV fuels. Only gasoline is considered as fuel for the supermini, mid-size and SUV ICVs/HEVs, whilst only diesel is considered as fuel for the LGV ICV/HEV – the properties of these two fuels used in this work are shown in Table A4 (JRC/EUCAR/CONCAWE, 2008; Samaras and Meisterling, 2008; authors' analysis).

In the 2015+ timeframe, the RED (EU Directive, 2009) for the EU and the Energy Independence and Security Act (EISA) (U.S. Congress, 2007) for the U.S. will be in force, which mandate the use of bio-fuels and the minimum GHG emissions saving required of them compared with conventional gasoline and diesel fuels. Accordingly, two bio-fuel scenarios, namely 'low-reduction' and 'high-reduction', are considered in this work. Table A5 shows the market share and GHG emissions saving of bio-fuels in these two scenarios. An average value of 4% is subsequently used for the EU and 5% for the U.S., giving an average GHG emissions intensity of 83.5 g CO_2eq/MJ (EU) and 91.2 g CO_2eq/MJ (U.S.) for both gasoline and diesel containing bio-fuels.

A.4.2. Tank-to-Wheels

A.4.2.1. Engine and vehicle modelling. Extensive vehicle simulation has been carried out for the four selected vehicle pairs to calculate

Table A4
Gasoline and diesel fuel properties.

Fuel	Density (g/L)	Lower heating value (J/g)	Carbon weight fraction (%)	WtW ($g\ CO_2eq/MJ$)
Gasoline	746.5	42.9	86.9	87.0[a]/96.0[b]
Diesel	835.0	43.2	86.0	87.0[a]/96.0[b]

[a] 100% fossil fuel for the EU-27 region (EU Directive, 2009; JRC/EUCAR/CONCAWE, 2008) – the Renewable Energy Directive (RED) (EU Directive, 2009) uses 83.8 g CO_2eq/MJ as the default value for diesel and gasoline (i.e., the fossil comparator to be used as the baseline). However, the literature (e.g., JRC/EUCAR/CONCAWE, 2008; LBST E3 Database, 2011) suggests a range of values, of which 83.8 seems to be on the low side. Therefore, the authors believe that a value of 87 is more appropriate for this work.
[b] 100% fossil fuel for the U.S. and California (CARB, 2009).

Table A5
Market share and GHG emissions saving of bio-fuels in different regions in the 2015+ timeframe,

	U.S.		EU-27	
	Low-reduction (%)	High-reduction (%)	Low-reduction (%)	High-reduction (%)
Market share by energy	5	10	10	15
GHG emissions saving	35	50	30	40
Total GHG saving	**1.75**	**5**	**3**	**6**

NOTE 1: no particular bio-fuels are investigated, because the potential complexity of methodological issues (allocation/substitution, land use change, etc.) and variety of pathways (origin of feedstock, agricultural and conversion processes, etc.) is beyond the scope of this study.
NOTE 2**:** the authors acknowledge that the topic of marginal fossil fuels should be further researched. However, it is considered beyond the scope of this paper, because: (a) when taking the spatial and/or temporal average, we do not think the potential contrast between marginal and average fossil fuels would be as sharp as that between marginal and average electricity; (b) more importantly, the LCA energy use and GHG emissions of conventional vehicles are dominated by the TtW part, so even a significant change in the WtT part would have a limited impact on the WtW and full LCA results. In particular, regarding the potential variation of biofuels, in the chosen timeframe of 2015, we have taken into account the most likely average biofuel content and derived a total WtW GHG saving (4–5%) – in this context, even a 50% uncertainty in the GHG intensities of bio-fuels would only lead to uncertainty levels of a couple of per cent in the total WtW GHG saving.

their TtW energy use under a wide range of driving conditions (speed/load profiles, vehicle loading and accessory use), taking into account the technological evolution for both the ICVs and BEVs. For the HEVs, additional efficiency improvement via kinetic energy recovery (KER) is considered.

Shell's own internal combustion (IC) engine model (Ma et al., 2011) and the open-source vehicle simulation software ADVISOR 2002 (Wipke et al., 1999) are used to calculate vehicle energy consumption under a given speed/load profile, i.e., drive cycle, along with the following assumptions, which help achieve like-for-like comparisons between the vehicle pairs:

- The design and technologies of BEVs are not expected to change significantly between now and 2015, given the scale of the near-term market, their relatively high purchase price and the time and investment required to bring new BEV design and technologies to commercial viability. The authors believe that in the timeframe of 2010–2015, BEV manufacturers and suppliers will likely focus on cost reduction, marketability, reliability and innovative business models, rather than significant technological improvement.
- For the 2015+ ICVs, the following improvements over their current counterparts are modelled, some of which depend on the vehicle segment:
    - Engine downsizing – in this work, this is achieved by maintaining the cylinder geometries while reducing the number of cylinders and increasing the power density, in terms of brake mean effective pressure (BMEP).
    - Engine technology – the main technological platform is maintained for most 2015+ ICVs (i.e., fuel injection, boosting, etc.), except that the gasoline engine for the 2015+ SUV is turbocharged instead of naturally aspirated.
    - Engine friction – the friction mean effective pressure (FMEP) is reduced by 10%, mainly due to improvement in engine design, lower-friction materials and higher-standard lubricants.
    - Accessory load – these may include fluid pumps, power-assisted steering, fans, heating, ventilation and air conditioning (HVAC) etc.; for the 2015+ ICVs, the basic mechanical accessory load drawn from the engine is reduced, mainly due to electrification of components and energy management (the level of reduction depends on the vehicle segment).
    - Vehicle weight reduction – due to engine downsizing and other weight reduction measures, the weight of 2015+ ICVs is reduced, by 6–11% depending on the vehicle segment.
    - Aerodynamic drag – the aerodynamic factor (drag coefficient times frontal area) is reduced by 10%, according to historic trend (Wikipedia, 2009).
    - Rolling drag – the tyre rolling resistance coefficient is reduced from 0.008 to 0.007, according to historic trend and interviews with vehicle original equipment manufacturers (OEMs) (Transportation Research Board, 2006; ConsumerReports, 2007).
    - Hybridisation – all 2015+ ICVs are assumed to have stop/start capabilities but no further hybridisation (i.e., no electric drive or significant regenerative braking).
    - For stop/start operations, the energy consumption at idle is first calculated then subtracted from the nominal energy consumption without stop/start operations.
- Because no detailed technical data (e.g., batteries, motor, etc.) are available for the modelled BEVs, a simplified simulation methodology has been adopted based on energy conservation. When a car is being driven on the road, the output power, P, consists of terms to resist the following: aerodynamic drag, tyre rolling drag (sliding drag as well if tyre slip occurs), gravity when ascending a slope, vehicle inertia when accelerating and power demand from car accessories. These terms are denoted as P_{aero}, P_{roll}, P_{grad}, P_{accel}, and P_{acc}, respectively in the equation below:

$$\begin{aligned} P &= P_{\mathrm{aero}}+P_{\mathrm{roll}}+P_{\mathrm{grad}}+P_{\mathrm{accel}}+P_{\mathrm{acc}}+P_{\mathrm{other}} \\ &= \tfrac{1}{2}\rho_{\mathrm{a}}C_{\mathrm{D}}A_{\mathrm{f}}v^3+Mg(\mu_1 v+\mu_2 v^2+\mu_3 v^3) \\ &\quad +Mgv\sin\theta+Mav+P_{\mathrm{acc}}+P_{\mathrm{other}} \end{aligned} \tag{1}$$

  where ρ_{a}=air density, C_{D}=aerodynamic drag coefficient, A_{f}=vehicle frontal area, v=vehicle speed, M=vehicle mass, g=gravity of Earth, μ_1, μ_2, μ_3=1st, 2nd and 3rd order rolling resistance coefficients (μ_2, μ_3 usually zero), θ=road gradient, a=vehicle acceleration rate, P_{other}=power imbalance unaccounted for, considered negligible.

Not shown explicitly in this equation is the energy transfer during braking or charging/depleting the battery. Energy used by P_{aero}, P_{roll}, P_{grad}, P_{accel} to get the car to a certain altitude and speed will either dissipate as heat, e.g., via normal braking and aerodynamic/rolling resistance, or be partly recovered, e.g., via regenerative braking and downhill coasting. Also, as the load of the drive cycle increases, the efficiencies of various vehicle components (IC engine, motor/inverter, etc.) improve as well, except that the efficiency of batteries may drop at high discharge rates and outside the range of state of charge (SOC) within which they are designed to operate.

For a defined BEV and a prescribed drive cycle, ADVISOR calculates the terms in Eq. (1) and then the total nominal energy required at the wheels throughout the drive cycle. Depending on the actual drive cycle, i.e., speed/load profile, different efficiencies are applied to the motor/inverter, transmission and batteries, and finally a fixed conductive charger efficiency of 90%[5] is

[5] This efficiency depends on factors including the vehicle charger design, charging rate and charging algorithms, etc., with 90% typically applicable for standard charging rates in a household; it may drop significantly under fast charging conditions.

Table A6
Efficiencies for BEVs.

Drive cycle	Regenerative braking (%)	Motor+inverter (%)	Gear (%)	Wheel+axle (%)	Battery (%)	Charger (%)
ECE	50	72	92	92	97	90
EUDC	50	85	92	94	90	90
NEDC	50	81	92	93	95	90
UDDS	50	78	92	93	97	90
US06	50	88	93	95	85	90

NOTE: apart from information revealed by OEMs, suppliers and automotive consultancies at conferences and seminars, an overall validation criterion for these technological measures is that for the 2015+ mid-size passenger car, the most dominant vehicle segment in Europe, the simulated standard vehicle-certification test result should fall just below the 2015 European Union mandatory target for each auto-manufacturer's fleet averaged CO_2 emissions from newly registered passenger cars (EU Regulation, 2009), i.e., 130 g CO_2/km with vehicle efficiency improvement features and 120 g CO_2/km with further contributions from measures such as bio-fuels and tyre pressure monitoring.

applied to arrive at the energy consumption from plug to wheels. Table A6 lists the efficiencies used for BEVs, derived from various publications (e.g., GCEP, 2006; Bandivadekar et al., 2008; Rantik, 1999; Matheys and Van Autenboer, 2005; Freyermuth et al., 2008; Nelson et al., 2007; Williamson et al., 2007) and ADVISOR libraries. A regenerative rate of 50%[6] is assumed for kinetic energy recovery (i.e., 50% of the braking energy, otherwise wasted as heat, is re-directed to the wheels) and the energy saving is subtracted from the total nominal energy required at the wheels.

For the LCA reported in this paper, additional assumptions/ simplifications are made as the following:

- For the EU, TtW results under the ECE and EUDC part of the New European Driving Cycle (NEDC) are used to represent urban and extra-urban driving, respectively.
- For the U.S., TtW results under the Urban Dynamometer Driving Schedule (UDDS) and the US06 cycle are used to represent urban and extra-urban driving, respectively.
- Two vehicle loading scenarios and two accessory use scenarios are simulated (Table A7).
- Only CO_2 emissions are calculated in the TtW analysis, because both CH_4 and N_2O emissions from the tailpipe are considered negligible (JRC/EUCAR/CONCAWE, 2008).

A.4.2.2. Model validation. The IC engine and vehicle models have been validated extensively against both Shell's own and externally published data (Ma et al., 2011); for the purpose of this work, further validation has been carried out for the vehicles (eight in total) that either are currently available on the UK market or have reported laboratory test results. Table A8 summarises the energy consumption results for these validated vehicles; the accuracy of the model is generally within 3%, with two ECE exceptions[7] (discrepancy up to 8%) and one EUDC exception (discrepancy up to 5%). Also shown in Table A8 as a reference is the GM Volt in BEV mode, which is considered in the same vehicle segment as the Mini with a higher curb weight around 1600 kg and probably slightly better aerodynamic design and tires – note that the Mini results from ADVISOR are slightly below the Volt test results, further validating the BEV model.

Table A7
Four driving scenarios.

Vehicle segment	Vehicle weight (kg)	Accessory load (kW)
Super-mini passenger	Standard/+75	Standard/+1
Mid-size passenger	Standard/+75	Standard/+2
SUV	Standard/+300	Standard/+5
LGV	Standard/+800	Standard/+3

A.4.3. Vehicle life cycle

A comprehensive life cycle inventory for the vehicle system would require a large amount of up-to-date primary data and much detailed LCA modelling, which could take a consortium of many interested parties up to 5 years (e.g., Sullivan et al., 1998). Furthermore, there is a general lack of data/information for the 2015+ vehicles to be studied. For these reasons, a simplified methodology is adopted, similar to those adopted by Bandivadekar et al. (2008), Schafer et al. (2006), Lane (2006), Zamel and Li (2006a, 2006b), Burnham et al. (2006) and Wang (1999):

- Production of raw materials – the composition of materials (weight percentage) needed to make a vehicle are estimated, and the associated energy consumption and GHG emissions are calculated based on data from the literature for grouped materials (Rydh and Sun, 2005; Schweimer and Levin, 2000; Zamel and Li, 2006a; Sullivan et al., 1998). The use of both virgin and recycled materials is included. Two vehicle material scenarios are considered, namely, regular-weight-material (RWM) and light-weight-material (LWM). In each scenario, the vehicle material composition is assumed to be the same for all vehicle segments. Almost all previous studies conclude that this phase is the most significant in the whole vehicle life cycle, and hence is the focus of this work.
- Vehicle manufacturing – most previous studies conclude or assume that this phase is significant in the whole vehicle life cycle; however, due to the very complex supply chain in the automotive industry and the associated difficulty in assessing the manufacturing processes of vehicle components and assembly, this is typically estimated as a linear function of vehicle mass. A scaling factor, in MJ/kg, and a GHG emissions factor, in g CO_2eq/MJ, are derived from the literature for energy use and GHG emissions, respectively.
- Vehicle distribution – this is assumed to be in the form of road transportation using diesel as the fuel. Average values of fuel

[6] This efficiency depends on factors including the integration and interaction between the electric and mechanical components, the speed/load profiles, vehicle weight etc. Extensive simulations with both BEVs and HEVs in ADVISOR show that 50% is generally applicable for kinetic energy recovery via drivetrain electrification. Other drivetrain systems, such as hydraulic, pneumatic or flywheel, may offer better recovery rate, e.g., up to 60–70% for the Flybrid system (Cross and Brockbank, 2009; Murphy, 2009).

[7] This is probably due to the intrinsic error in simulating vehicle idling – during the ECE cycle, a vehicle spends a considerable amount of time idling, more than that in the other drive cycles.

Table A8
Validation results for vehicle simulation.

ICV	Drive cycle	Fuel (L/100 km) Test	ADVISOR
2006 SmartForTwo gasoline	NEDC/ECE/EUDC	4.9/6.2/4.1	4.83/6.15/4.08
2008 Mini Cooper S gasoline	NEDC/ECE/EUDC	6.4/8.1/5.4	6.53/8.77/5.25
2007 Porsche Cayenne gasoline	NEDC/ECE/EUDC	12.9/18.5/9.8	12.62/18.33/9.35
2009 Ford Transit Connect diesel	NEDC/ECE/EUDC	6.2/7.4/5.6	6.38/8.05/5.43
		Electricity (MJ/km)	
BEV	Drive cycle	Test	ADVISOR
2006 Smart EV	NEDC	0.432	0.438
2009 Mini Cooper E	NEDC	0.504	0.518
2009 Mini Cooper E	UDDS/HWFET	–/–	0.485/0.560
2011 g Volt (Tate et al., 2008)	UDDS/HWFET	0.50/0.58	–/–

consumption and delivery distance are derived from the literature.

- Vehicle maintenance and repair – this phase is very dependent on the actual practice in real life and very little data exist in the open literature; however, almost all studies to date conclude or assume that this phase makes a relatively small contribution to the whole life cycle (fuel and vehicle), therefore this phase is estimated similarly to vehicle manufacturing, i.e., using a scaling factor.
- Vehicle end-of-life (VEOL) – this phase is also very dependent on the actual practice in real life and only a limited amount of data with large variability exist in the open literature; furthermore, it is unclear what the state-of-the-art disposal and recycling technologies will be for 2015+ vehicles, the VEOL treatment of which will not likely be carried out until 2030. However, again, almost all studies to date conclude or assume that this phase makes a small contribution to the whole life cycle (fuel and vehicle), therefore this phase is estimated similarly to vehicle manufacturing, i.e., using a scaling factor.

The GHG emissions factors used for the vehicle manufacturing phase, maintenance and repair phase and VEOL phase are determined by the energy mix and the respective emissions intensities of the energy sources, namely, electricity and diesel, on a WtW basis – energy use from other sources are considered negligible. The average conversion efficiency of primary energy to electricity is assumed to be 35%.

A range of plausible values have been investigated wherever possible for each key parameter used in the vehicle life cycle study, with a sensitivity analysis to identify uncertain factors with the most significance in the vehicle life cycle.

A.5. Sensitivity and uncertainty

The following parameters have been identified as the most important sources of uncertainty during the LCA:

- Vehicle life – current battery technologies limit the calendar life of BEVs to 8–10 years. It is conceivable that, after the EV battery becomes out of service, the rest of the BEV will be scrapped as opposed to the battery being replaced with a brand new one for economic and technical reasons. As a result, the vehicle life cycle GHG emissions would need to be re-distributed over 8–10 years rather than the 15 years assumed in this work, and consequently be up to double the values presented in this work on a per-km basis.
- Vehicle annual mileage – similar to vehicle life, this parameter directly and proportionally affects the per-km vehicle life cycle GHG emissions, in other words, the higher the vehicle annual mileage, the lower the vehicle life cycle emissions on a per-km basis.
- Marginal grid intensity – recent studies (McCarthy and Yang, 2010; Hawkes, 2010) suggest that the marginal grid intensity could vary by up to 20%, subject to large daily, seasonal and spatial variation as well as the actual load demand profile from electric vehicles.
- Driving pattern – as shown in the main text, the TtW energy use and GHG emissions are greatly influenced by the drive cycle, and vehicle and accessory loading. Under assumptions that the authors believe represent real-world driving, vehicle loading (passengers, cargo, etc.) seems less influential than drive cycle and accessory loading. While the sensitivity of the final results to these parameters is very high, the potential uncertainty is considered low because the simulation tools and results have been extensively validated.
- Material recycling rate – between a recycling rate of 0% and 100%, the vehicle life cycle GHG emissions could vary by 50–60%.

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