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ASSESSING AND MANAGING LIFE CYCLES OF ELECTRIC VEHICLES

A new hybrid method for reducing the gap between WTW and LCA in the carbon footprint assessment of electric vehicles

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Abstract

Purpose The well-to-wheel (WTW) methodology is widely used for policy support in road transport. It can be seen as a simplified life cycle assessment (LCA) that focuses on the energy consumption and CO_2 emissions only for the fuel being consumed, ignoring other stages of a vehicle's life cycle. WTW results are therefore different from LCA results. In order to close this gap, the authors propose a hybrid WTW+LCA methodology useful to assess the greenhouse gas (GHG) profiles of road vehicles.

Methods The proposed method (hybrid WTW+LCA) keeps the main hypotheses of the WTW methodology, but integrates them with LCA data restricted to the global warming potential (GWP) occurring during the manufacturing of the battery pack. WTW data are used for the GHG intensity of the EU electric mix, after a consistency check with the main life cycle impact (LCI) sources available in literature.

Results and discussion A numerical example is provided, comparing GHG emissions due to the use of a battery electric vehicle (BEV) with emissions from an internal combustion engine vehicle. This comparison is done both according to the WTW approach (namely the JEC WTW version 4) and the proposed hybrid WTW+LCA method. The GHG savings due to the use of BEVs calculated with the WTW-4 range between 44 and 56 %, while according to the hybrid method the savings are lower (31–46 %). This difference is due to the GWP which arises as a result of the manufacturing of the battery pack for the electric vehicles.

Conclusions The WTW methodology used in policy support to quantify energy content and GHG emissions of fuels and powertrains can produce results closer to the LCA methodology by adopting a hybrid WTW+LCA approach. While evaluating GHG savings due to the use of BEVs, it is important that this method considers the GWP due to the manufacturing of the battery pack.

Keywords Battery · Battery electric vehicle · BEV · Carbon footprint · GHG · GWP · LCA · Well-to-wheels

1 Introduction

1.1 Background

Political interest in decarbonizing the world economy is growing. On December 2015, Paris will host the UN international summit aiming at replacing the Kyoto protocol with a new binding agreement on climate change. Meanwhile, China (APEC 2014), the European Union (2014) and the USA (USA 2010; APEC 2014) agreed to reduce their greenhouse gas (GHG) emissions by year 2030, and the environmental strategies of many governments around the world are converging towards this target. A particular promising policy that can reduce GHG emissions in the transportation sector is supporting the replacement of conventional vehicles, based on internal combustion engines (ICE), with electric vehicles (EV). According to the German Advisory Council on Global Change, the majority of final energy consumption in the transport sector across the EU-27 will be saved by 2050 as a result

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of the widespread introduction of electric vehicles (WBGU 2011). In order to assess the impact of GHG and energy saving policies, policy makers need to consider sound and shared scientific methodologies allowing comparisons among "green" and conventional technologies. Since electric energy and fossil fuel pathways are very different, they need to be compared from the perspective of a life cycle assessment (LCA). At the regulatory level, well-to-wheel (WTW) analysis is the dominant LCA methodology used to assess GHG and energy savings in transport. WTW methodology is used for example by the European Union for the Fuel Quality Directive (2009a) and for the Renewable Energy Directive (2009b), in the USA, the Environmental Protection Agency bases its regulatory actions on the WTW approach (EPA 2007) of the GREET model (ANL 2014), and also in China, WTW is used to assess policy options (Huo et al. 2012).

WTW methodology can be seen as a quite simplified LCA, designed to assess only the energy consumption and the GHG emissions of road transport fuels without considering, for example, the impacts of manufacturing and decommissioning of the vehicles themselves. This limited set of considerations makes the WTW particularly suitable to policy support, even if it can give figures different to those obtained from a rigorous LCA as carried out according to the ISO 14040 standard series (ISO 2006). Environmental policies designed on a simplified data set, as it is the WTW now, can overlook relevant elements, particularly in a future perspective, when a larger share of renewable energy sources will be integrated into the EU electric grid, and the impact of the GHG emissions due to the production of EVs will be more important than today, compared to the GHG emissions from the production of electric energy.

1.2 Purpose

In this paper, the advantages and drawbacks of the WTW methodology when compared with the LCA approach are summarised. The authors will analyse in depth the data set presented in the well-to-tank (WTT) study produced by the JEC (JRC-EUCAR-CONCAWE)[1] research collaboration (JEC 2014a), detailing the EU27 electricity mix pathway and comparing the results with the equivalent LCA figures. The authors evaluate GHG savings due to the use of EVs instead of ICE vehicles, both with the WTW methodology and with an LCA approach, and try to understand how wide the differences are and possible steps to reduce them. Reducing the gap between the two methodologies can assist data intercomparison from different geographical regions and sources, allowing policy makers to rely on wider, more reliable databases while maintaining a comparatively simple and useful assessment method. An important purpose of this article is also to bridge cultures, trying to reduce the methodological distance between the LCA and the WTW scientific communities. To this scope, the authors have chosen a popularising approach, maybe indulging in explanations that can seem too long to the expert of one field, but that are maybe useful to the experts of the other field to better understand the pros and cons of the two methods and, consequently, to better appreciate the potential applications of the hybrid WTW+LCA method proposed in this paper.

2 Methodology

2.1 Comparison of WTW and LCA

The well-to-wheel (WTW) methodology considered in this paper is the WTW version 4 (WTW-4) developed within the JEC (JEC 2014b). This method allows to quantify the energy required for and the GHG emissions resulting from the production, transport and distribution of conventional and alternative road transportation fuels (well-to-tank or WTT), and also to quantify the efficiency of different powertrains (tank-to-wheel or TTW). Compared to a comprehensive attributional life cycle assessment (LCA) approach, WTW considers only parts of the LCA impact categories "energy consumption" and "GHG emissions" necessary for the production of a functional unit (i.e., one MJ of fuel or a kilometer driven by a vehicle). For example, in the WTW approach, the material consumptions for the fuel production process are not taken into account, neither are the water requirement, acidification or emissions of pollutants if these do not affect the GHG equivalent emissions. Moreover, in WTW there is no calculation of the energy and GHG which occur during the construction or decommissioning of plants and vehicles.

In Fig. 1, a simplified scheme of the different boundaries of LCA and WTW studies when quantifying the energy cost of fuel use are presented. Whereas WTW mainly focuses on the midstream ("in operation") phase, the LCA considers more activities in the upstream chain and, with the end-of-life management, also downstream (non midstream is also called background data). One of the main differences between WTW and LCA calculations that cannot be easily displayed in a scheme like Fig. 1, is the implementation of time scales in LCA, at least for the main product (here: a vehicle). All flows under LCA will be standardised for certain product lifetimes or at least a lifetime under which different LCA results may be compared. For a vehicle, LCA calculations reported are usually based on 100,000 to 200,000 km of driven distance, ecoinvent database suggests 150,000 km (Del Duce et al. 2014) and in exceptional cases, this can reach 240,000 km (Nordelöf et al. 2014). Accordingly, WTW-4 (JEC 2014b) defines a "lifetime of at least 160,000 km" for an electric

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[1] EUCAR: European Council for Automotive R&D; CONCAWE: the oil companies' European association for environment, health and safety in refining and distribution.

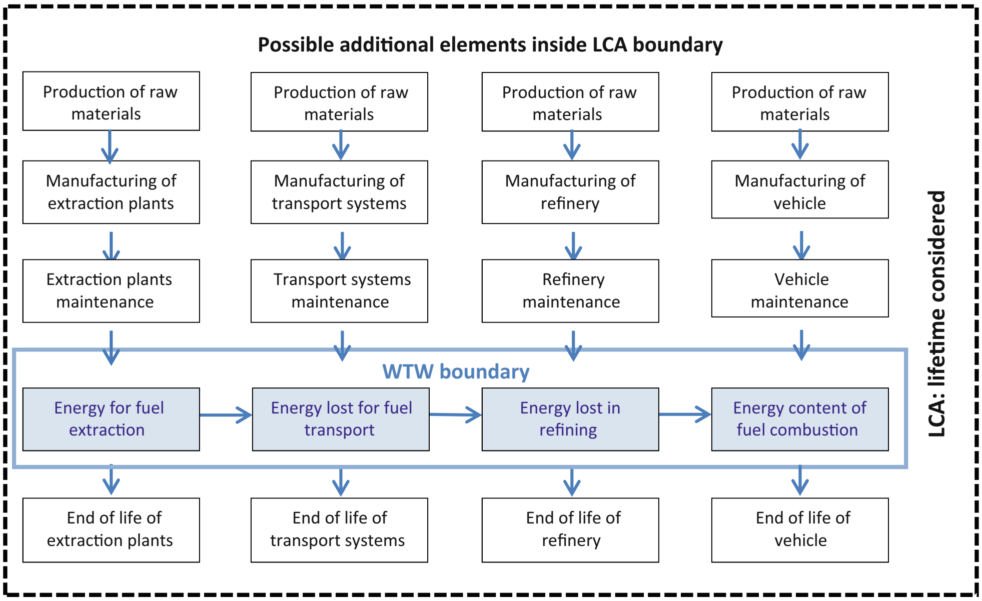

Fig. 1 Schematic representation of WTW boundaries while assessing the "energy content" of a fuel associated with CO_2eq-expenses, and completed by possible additional elements of an LCA system describing a vehicle

vehicle. In WTW, the term "lifetime" is used to specify the period in which the vehicle is expected to operate under specific efficiency parameters. The inventory analysis inside an LCA, however, also contains periods before and after the practical use or the operational life of a product.

Within the timeframe of an LCA, the biggest challenge is to comprehensively collect all material and energy expenditures as well as distances covered through transportation (the life cycle inventory) once the goal and scope (the boundaries) have been defined. The WTW methodology differs from the LCA in the sense that WTW focuses on the operational phase of the vehicle in as strict a sense as possible (in WTW-4: see JEC 2014b).

There are some criticisms to this approach. Nordelöf et al. (2014), for example, argue that in WTW, a BEV charged with renewable electricity seems to have "almost no environmental impact." While setting environmental policy targets, the main interest is, often, on energy consumption and GHG emissions only. With this aim WTW makes it easier in general to compare different fuels and powertrains while sacrificing a small loss in precision when compared to a full LCA. This is quite intuitive in the case of biofuels: if we want to assess the GHG savings of vehicles using biofuels instead of fossil fuels it is necessary to compare their GHG emissions. Since the infrastructures for using fossil fuels and biofuels are similar (e.g., road infrastructures are the same) and the vehicles burning fossil fuel can burn also the biofuel blends (from 7 to 10 % today in Europe)[2] it is possible to say that, while comparing the carbon footprint of biofuels with that of fossil fuels, the WTW methodology is a good approximation of the LCA.

Another difference between WTW and LCA scope is that WTW provides an "open, universal" attempt to quantify the global warming potential (GWP) of driving e.g., an electric car. This concept must provide a single average GWP for Europe's electricity production, while, as it is correctly noted by e.g., Ma et al. (2012) and Nordelöf et al. (2014), in European countries with an electricity production based on fossil resources, electric driving can be related to (much) higher GHG emissions during the operation phase (when compared to using fossil fuels). However, LCA modelling results often have a particular regional validity (e.g., Goedkoop et al. 2009). Even with this consideration, the authors wish to keep the open character of WTW, because for topics such as, for example, the condition of electricity charging local peculiarities may occur for which specific life cycle impact (LCI) data might not be available. For example: electricity produced in the northern states of Germany is already mostly of renewable origin, because of the dominance of windmills in that region, although Germany's overall electricity carbon impact shows only average performance; or a BEV driven in a country with >90 % coal-fired power plants in electricity production, may nevertheless be charged from a local photovoltaic device.

2.2 GHG emissions from the EU electric energy mix

The focus of this article is to compare LCA results with WTW results describing the Global Warming Potential (or GHG emissions) due to the use of electric vehicles.[3] The JEC WTT-4 report presents figures detailing the GHG intensity

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[2] The standard EN590 for diesel fuels allows 7 vol.% FAME, while the EN228 petrol allows up to 10 vol.% ethanol.

[3] In this paper, the authors will not compare WTW with LCA data describing the primary energy consumption because this would be redundant, since the primary energy consumptions are linked to the GHG emissions by mean of the IPCC (2006) emission factors.

of the average kilowatt hour of electric energy supplied in the European Union (JEC 2014a). Unfortunately, not all the boundary conditions and working hypotheses were provided in the JEC (2014a) report. In order to allow LCA experts to better compare WTW data and boundary conditions with their own work, the authors summarise here the main data presented in the WTW-4 report, and integrate them with additional explanations on the hypotheses and boundary conditions adopted. The main assumptions used to calculate the EU electric mix in WTT-4 were as follows:

- Temporal framework: year 2009;
- Geographic boundaries: the EU27 Member States;
- CO_2 credits assigned for heat produced by combined heat and power (CHP) plants;
- IPCC 2006 emission factors calculated for the 100 years horizon (IPCC 2006);
- Greenhouse gases considered for global warming potential calculations: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)
- Upstream emissions calculated by the JEC with the E3 DB model (LBST 2014)

For each of the EU27 MSs the authors considered statistical data on primary energy consumed in input and the electrical energy output produced by power plants (IEA 2011a, b, c). This has been done for every kind of fuel or energy used for producing electric energy, both for conventional electric and CHP plants.

CHP plants do not use all the primary energy input for electricity production, but part of this energy goes for heating applications; so the authors considered a GHG credit for the heat produced in output from CHPs according to the "substitution" allocation method adopted in WTW. The heat produced from the CHPs (statistical data from IEA 2011c) has been considered as replacing a thermal heating system with average heating efficiencies of 85 % for coal, lignite, coke, peat, biomass and waste, and 90 % for natural gas, biogas, LPG and oil products, respectively. Data quality problems can cause the substitution approach to underestimate the carbon intensity of electric CHP plants (IEA 2013).

For nuclear power plants and renewable energy sources, there is a different form of energy input compared to fossil fuel primary energy input. According to the main international statistical bodies (IEA, EUROSTAT, IAEA) different energy forms are compared by converting the electric energy produced from nuclear or renewables into an *equivalent* primary energy value by adopting the average thermal efficiency method (see, i.e., IAEA 2007). The average thermal efficiency for nuclear power plants has been considered 33 %, for geothermal energy 10 % and for the other renewable sources (solar, wind, hydro) 100 %.

The upstream emissions and energy losses due to the extraction and transport of the fuels to the power plants has been calculated on the basis of the JEC data which uses the database "E3 DB" (LBST 2014).

The total GHG emissions due to the gross electric energy production is the sum of two contributions, as illustrated in Fig. 2: the upstream emissions and the combustion emissions, with the combustion emissions obtained by multiplying the 2006 IPCC emission factors to the primary energy consumptions. According to these data sources and hypotheses the GHG emissions caused by a kilowatt hour of gross electric energy produced in the EU-27 in 2009 were equal to 457 g CO_2eq.. This figure refers to the production of a unit of *gross* electric energy, without considering the own energy losses of power plants. According to the statistical sources we used (IEA 2011a, b,c) the *gross* electric energy production (for the EU27, in 2009a, b) was 3.170 TWh, while the total *net* production of electric energy (also: "at the station busbars") was 3.046 TWh. Consequently, the production of electric energy (represented in Fig. 3) causes 476 g CO_2eq/kWh.

Another issue to be considered is the energy consumed by pumping plants in order to store water in the higher elevation reservoirs of hydropower plants. After the pumping losses deduction the energy provided to the net is 3004 TWh, so the GHG content of 1 kWh of electric energy (in EU27, in 2009a, b) was 482 g CO_2eq.

The difference between the electric energy after pumping losses and the electric energy "supplied to the net" is the import–export balance. However, the origin of electric energy imported/exported is not statistically described. So, it is not easy to know, for example, if the electric energy imported by a member state is produced from coal or from hydropower. This would change, in general, the emission calculations, but in our case, the focus is on emissions of the EU27 market as a whole, and it is possible to demonstrate that there is only a difference of less than 0.5 % between considering EU-27 net imports (15 TWh according to the IEA 2011a, b, c) on the calculation of energy supplied. Consequently, the value of 482 g CO_2eq/kWh represents a good approximation of the average emissions associated with the electrical energy supplied to the European grid.

By following the electrical pathway along the transmission and distribution network and identifying the power losses, it is possible to assess the GHG intensity of electrical energy at high voltage (HV), medium voltage (MV) and low voltage (LV). The following input data set and assumptions were adopted, and are similar to those in the ecoinvent database (see the ecoinvent update v.2.2 as made by Itten 2012).

- Total power losses (sum of transmission and distribution): 188 TWh (6.3 % of energy supplied). Source: IEA (2011a, b)

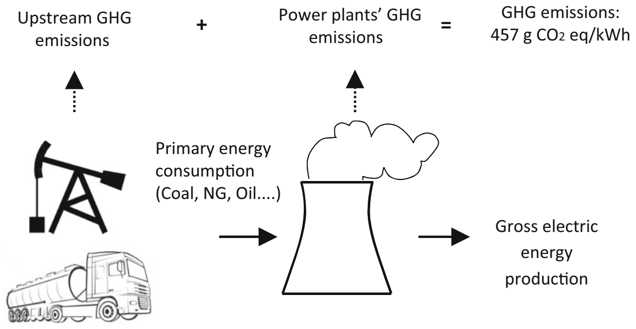


Fig. 2 Main scheme of the electric energy mix calculations in the WTW-4 and data set adopted

- HV transmission power losses: 1.5 % of energy supplied (ENTSO-E 2011); the authors consider this percentage to be reliable also for the EU-27, year 2009 network.
- MV-LV repartition of losses according to AEEG (2012): "(cumulated losses) at 220 kV = 1.1 %; at MV = 4.7 %; at LV = 10.4 %." This power loss repartition is assumed to be the same for all the EU27 MS. (Similarly, in the ecoinvent data base, the Swiss dataset is used for all the distribution networks).

According to the dataset above, the power losses in the electricity network can be split into three components: losses at HV, MV and LV, and represented in terms of energy efficiency as in Fig. 4.

With these input data, it is possible to calculate the GHG intensity of 1 kWh of electric energy at the various steps of energy voltage distribution. The results, presented in the WTT report (JEC 2014a), are summarised here in the WTW-4 column of Table 1. The GHG intensity of the average kilowatt hour of electricity consumed at low voltage in EU27 in 2009 was 540 g CO_2eq/kWh. However, it is important to keep in mind that this is just an averaged value. Since power production can rely on very different energy sources, in different EU countries, in some geographic regions the GHG intensity can be much lower (e.g., 30 g CO_2eq/kWh for Sweden) or higher (e.g., 1200 g CO_2eq/kWh in Poland).

In Table 1, WTW-4 data describing the EU27 electricity mix in 2009 is compared to results from the main LCA literature sources. Some figures are calculated on slightly different boundary conditions with respect to the WTW approach, for example, by using statistical data of year 2008 or 2010 instead of year 2009, or considering different electricity networks (UCTE instead of EU27). However, this comparison shows a reasonable level of consistency between WTW-4 and the LCA literature. The GHG intensity of a kilowatt hour of electrical energy at LV, for the EU27 in 2009 according to the WTW-4 (540 g CO_2eq/kWh) is practically the same value as that calculated using a LCA methodology) by Itten et al. (2012) for the year 2008 in EU27 (523 g CO_2eq/kWh). Similarly, the GHG intensity at LV calculated from the "ecoinvent" 2.2-database is, for the UCTE network in year 2010: 594 gCO_2eq/kWh; while results of the "GaBi" DB, for the EU27 and year 2009 are equal to 485 g CO_2eq/kWh. If an uncertainty of 10 % between the WTW-4, "ecoinvent" and "GaBi" data sets is considered acceptable, there would be no statistical difference between these literature sources.

So far, it can be concluded that the GHG intensity of the EU27 electric mix for the year 2009 as calculated according to the WTW methodology is consistent with LCA literature datasets.

2.3 GHG emissions of battery electric vehicles. The WTW method

Using the GHG intensity of the average kilowatt hour of electricity it is possible to assess the GHG emissions per km from the average EU battery electric vehicle (BEV) according to the Formula 1

$$\text{BEV\_emissions} = \text{GHG\_electric\_mix} * \text{BEV\_consumption}/100 \qquad (1)$$

Where:

BEV_emissions	are the GHG emissions per kilometer of a BEV, expressed in [g CO_2eq/km]
GHG_electric_mix	is the GHG intensity of the electric energy mix [gCO_2eq/kWh]
BEV_consumption	is the BEV electric energy consumption, in [kWh/100 km]

The WTW-4 study (JEC 2014b) considers as a reference vehicle, an averaged or "virtual" car representing the most widespread European C-segment compact five-seater European sedan, six speed manual transmission and front wheel drive available in year 2010 (JEC 2014c). For gasoline engines, the reference vehicle is equipped with a 1.4-l direct injection spark

Fig. 3 WTW-4 steps considered for to the production of electric energy and GHG emissions

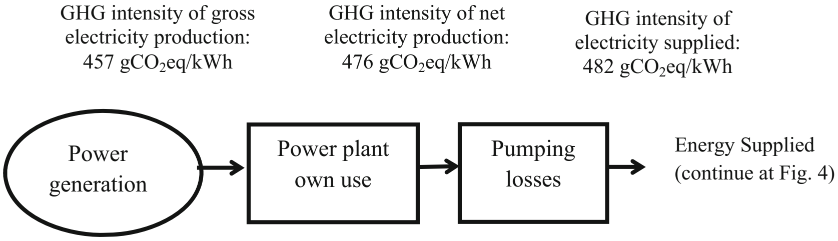
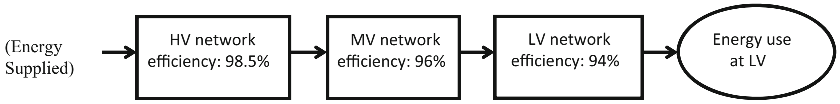


Fig. 4 WTW-4 efficiency of the EU27 electric network in 2009



ignition (DISI) ICE, while for diesel engines with a 1.6-l direct injection compression ignition (DICI) ICE. The BEV competing with these average ICE vehicles has a Li-ion battery pack weighting 200 kg and offering a range of 120 km along the New European Driving Cycle (NEDC) cycle. Assuming an electricity consumption of 14.5 kWh/100 km and a target range of 120 km, results in a required battery capacity of 17.4 kWh, which is in accordance to usually smaller BEV on the market (Faria et al. 2013).

The main characteristics of the vehicles considered in this paper are summarised in Table 2. The weights reported in Table 2 include the driver and the fuel tank filled to a 90 % level. Fuel consumption figures are evaluated on the basis of the current European-type approval cycle NEDC. The BEV consumption is measured according to the UN ECE 101 (2005) regulation, so it also includes the charging losses occurring during the "slow" charge procedure (called "normal overnight charge" in the UN ECE 101), by using the on board charger of the BEV. For more detail, please refer to the tank-to-wheel study (JEC 2014c).

Table 1 GHG emissions from the EU electricity mix according to the WTW-4 and LCA sources

GHG emissions at various steps of production and distribution of electricity	WTW-4 based on EU27, year 2009 (JEC 2014b) [g CO$_2$eq/kWh]	Itten et al. (2012) based on EU27, year 2008 [g CO$_2$eq/kWh]	Ecoinvent 2.2, year 2010, UCTE[a] grid, modelled[b], [g CO$_2$eq/kWh]	GaBi based on EU 27, 2009 (PE 2012) [g CO$_2$eq/kWh]
GHG intensity of gross power generation	457	N/A	N/A	N/A
GHG of net power generation	476	464	516	N/A
GHG of power supplied to the network	482	N/A	N/A	N/A
GHG of electricity consumed at high voltage	490	481	523	N/A
GHG of electricity consumed at medium voltage	508	490	531	462
GHG of electricity consumed at low voltage	540	523	594	485

N/A data not available in the cited bibliographic source

[a] The UCTE electric network differs from the EU27 mainly because it does not consider the Northern EU countries such as Sweden, UK, the Baltic republics, Romania and Bulgaria. The difference in GHG intensity of a kilowatt hour calculated for EU27 and UCTE is about 5 % (Itten et al. 2012)

[b] Data generated by a separate Umberto software model simulating the carbon footprint of 1 kWh electricity and based on the following ecoinvent 2.2 modules (top down): "electricity, production mix UCTE", "electricity, high voltage, production UCTE, at grid"; "electricity, medium voltage, production UCTE, at grid" and "electricity, low voltage, production UCTE, at grid", respectively

The electric consumption of the average BEV considered in the WTW-4 report (JEC 2014b) is 14.5 kWh/100 km. According to Formula 1 and considering the GHG content of the EU27 electric mix (540 g CO$_2$eq/kWh at LV) the average GHG emissions of an average BEV are 78.3 g CO$_2$eq/km. Detailing the GHG emissions for individual member states is not in the scope of the JEC WTW and would present some methodological drawbacks (e.g., uncertainty due to import–export and data quality of CHP plants). However, to give an idea of the geographic variability of this number, in Sweden, the use of BEV would produce only 3 g CO$_2$eq/km while in Poland, about 170 g CO$_2$eq/km. According to the WTW-4, the use of BEV in countries relying on big shares of nuclear or renewable electricity, would be really a green solution, while, in countries with an unfavourable electric mix, electric cars would not be greener than using a new generation gasoline ICE car.

In Table 3, a comparison is made between the BEV's GHG emissions to those emissions from conventional ICE vehicles based on data from the WTW-4 report (JEC 2014b). The GHG savings due to the use of a BEV varies between 50 and 60 %, depending on the fuel/vehicle to which the BEV is compared to. The use of biofuels instead of neat fossil fuels at the blending levels commonly available in the EU markets (5 to 7 %) does not significantly affect the GHG savings from BEVs.

2.4 GHG emissions of battery electric vehicles. The hybrid WTW+LCA method

The proposed method aims at adopting the main hypotheses of the WTW methodology, in order to keep the relatively simple WTW approach, but integrating them with specific LCA data. In this section, the specific LCA data to be merged with the WTW-4 data set (JEC 2014b) will be discussed, while considering also universally valid LCA findings on GWP associated with the electric car's life cycle. This approach will be called "the hybrid WTW+LCA method."

It is considered that the well-to-tank results give, for the electric energy mix, values comparable to the main LCA datasets (see Table 1). Therefore, according to the simplified hybrid WTW+LCA method, it is suggested that the GHG

Table 2 Main parameters of gasoline, diesel and BEV vehicles. WTW-4 data (JEC 2014b)

Vehicle	Engine	Consumption	Weight	Tank capacity/ range
Battery electric vehicle	90 kW electric	14.5 kWh/ 100 km	1365 kg	120 km
Gasoline ICE	1.4 l DISI ICE, 90 kW	6.3 l/100 km	1310 kg	55 l
Diesel ICE	1.6 l DICI ICE, 88 kW	4.5 l/100 km	1370 kg	55 l

emissions due to the use of a BEV is simply the sum of its WTW emissions with specific LCA emissions for the manufacturing of the vehicle, expressed in the same measuring unit (g CO_2eq/km).

The end-of-life (EOL) aspects of vehicles are considered according to the following notes. Firstly, the ISO 14,044 standard recommends an LCA system expansion/substitution to quantify the effects of the recycling processes. This would be better than a simple “cut-off-method” which does not quantify the impacts of recycling processes (Althaus and Bauer 2012). At the same time, cut-off- and system extension/substitution-attempts seem to deliver comparable results in the life cycle modelling of electric cars (Habermacher 2011; Althaus and Bauer 2012). Usually, during LCA modelling of electric cars, EOL is simulated by alternatively both quantifying system extension/substitution and cut-off, so reported impacts of, e.g., battery production includes EOL (Notter et al. 2010; Habermacher 2011). Habermacher (2011) separately quantified the disposal of the electric car as an EOL scenario, resulting in a cost of up to 4 g CO_2eq/km (calculated from Habermacher 2011), which is, however, less then 5 % of the overall GWP of a compact BEV. Faria et al. (2013) confirmed this finding. Recycling the car (substitution assumption) instead of disposal can result in a positive GWP credit (Habermacher 2011).

The highest footprints caused in the manufacturing process of a BEV are (in this order) caused by the glider,[4] the battery and the drivetrain (Habermacher 2011).

Should the impact of the glider manufacturing be considered here, as it is usual in LCA? Not necessarily: First, gliders of BEVs and ICE vehicles (ICEVs) are very similar as shown in almost all LCA publications, as long as identical vehicles are compared in a combustion engine and electric version each (Helmers and Marx 2012). Implementation of the glider therefore would not significantly change the comparison of BEVs and ICEVs. Moreover, a glider does not necessarily have to be produced to allow electric driving. In a technical conversion, a used ICEV can be electrified keeping the glider and allowing electrical driving for a “second” vehicle’s life offering minimal lifetime carbon footprints (Helmers and Marx 2012).

An apparent inconsistency with LCA literature that can be identified in the WTW-4 assumptions of Table 2 is that the standard BEV outlined has only little excess curb weight compared to the ICEV. Actually, BEVs are usually heavier than ICEVs. In a project converting an ICEV-type SMART from combustion engine to electric, the electric engine almost equaled the weight of the replaced combustion engine (Helmers and Marx 2012). In a later project, this was confirmed by converting a GOLF-type car from combustion engine to electric. This indicates that the weight of the battery is an additional mass. According to Habermacher (2011), the error caused by underestimating a glider weight is in the order of 3 g CO_2eq/km or 3 %, respectively, over the life cycle. Considering this low number, and in order to keep the model as simple as possible, the authors have decided to keep the WTW-4-assumptions and to neglect this error.

Carbon footprints of drivetrain production are contradictory as reflected in literature: Habermacher (2011) reported higher drivetrain carbon footprints for ICEVs compared to BEVs, while Held and Baumann (2011) showed a negligible GWP excess for the electric drivetrain production. Notter et al. (2010) quantified an almost identical GWP for both the ICEV and BEV drivetrains. Hawkins et al. (2012) found a higher carbon footprint due to the electric powertrain production in the order of 7–11 % of the whole BEV compared to an ICEV. Considering the inconsistent nature of these datasets, it was decided to neglect the additional footprint of BEV drivetrain production.

The emissions impact of battery production, however, comes in addition. The WTW-4 suggests a battery of 200 kg weight (Table 5–2 in JEC 2014b), which is not too big realising that even a SMART needs a battery of 160 kg size to enable an electric range of 100 km (Helmers and Marx 2012). In contrast, it is noted that in several LCA studies, the sizes of batteries presumed were bigger than necessary causing a higher GWP (Helmers and Marx 2012). A number of papers have been published quantifying the carbon footprint of battery production and revealing a wide range in results. The data of six studies were reviewed by Helmers

Table 3 GHG emissions of BEV and ICE vehicles in operation

	WTW emissions (JEC 2014a, b, c) [g CO_2eq/km]	GHG saving of BEV [%]
Battery electric vehicle	78.3	–
ICE gasoline (neat)	178	56 %
ICE diesel (neat)	145	46 %
ICE diesel with 7 % biodiesel (rapeseed)	139	44 %

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[4] Glider: a car without the powertrain (Del Duce et al. 2014)

and Marx (2012) resulting in a range of emissions of 52–291 kg CO_2eq/kWh of a Li-ion battery (mean: 151 kg CO_2eq/kWh). These varieties were not mainly due to different Li-ion chemistries but due to different modelling approaches (top down vs. bottom up). In a more recent and comprehensive study, Ellingsen et al. (2014) reviewed results between 38 and 338 kg CO_2eq/kWh for the production of the battery, and added 172–487 kg CO_2eq/kWh from their own study. It was decided here to calculate a mean from Ellingsen et al.'s (2014) data giving a figure of 168 kg CO_2eq/kWh.

Returning to WTW-4-definitions, the lifetime of an electric car was adjusted to 160,000 km (JEC 2014b). This is well in agreement with assumptions in LCA reports: Notter et al. (2010), for example, based their calculations on a battery lifetime of 150,000 km. Relating the 168 kg CO_2eq/kWh to a lifetime of 160,000 km and to the battery capacity of 17.4 kWh (as calculated from WTW-4 data), for the battery manufacturing, it is necessary to consider an additional footprint of 18.3 g CO_2eq/km (168.000 g CO_2eq $kWh^{-1} \times$ 17.4 kWh/160,000 km) which is well reflected by data from literature (11–31 g CO_2eq/km, as reviewed by Ellingsen et al. 2014).

3 Results and discussion

According to the hybrid WTW+LCA method presented in this article, this battery impact (18.3 g CO_2eq/km) has to be added to the 78.3 g CO_2eq/km (Table 3) caused by the electricity consumption occurring during the operation phase. The result is 96.6 g CO_2eq/km for the standard-electric car according to WTW-4 definitions of Table 2.

The GHG emissions from BEV and ICE vehicles calculated according to the hybrid WTW+LCA methodology and the data sources cited earlier provide the results as shown in Table 4. In order to better visualise emissions and GHG savings from the use of BEVs, these results have been represented also in graph form (see Fig. 5).

By adopting this WTW+LCA hybrid method, the GHG emissions savings from the use of BEV is lowered by 10–13 %; comparing BEV and gasoline ICE vehicles using the pure WTW method resulted in GHG savings of 56 % (Table 3). Using the hybrid WTW+LCA method the GHG savings are reduced to 46 % (Table 4).

3.1 Limitations

The authors wish to point out that the two methods (i.e., life cycle assessment and WTW) need to be blended carefully. LCA offers impact quantification over a life cycle (a defined lifespan), attributed with strict context-specific aspects. WTW instead quantifies the carbon impact and energy consumption due to the process of driving a vehicle, and this is carried out using EU averaged data. While driving a vehicle, energy is continuously consumed, not the vehicle itself, which can have a lifetime of up to 563,000 km (Nordelöf et al. 2014) or be converted to another fossil fuel or to electric driving. In this context, while adding LCA data of battery manufacturing to the WTW, it is like the battery of a BEV was part of its fuel, because the battery is "consumed" to an extent after a certain number of recharging cycles. Summarising, the "life cycle" suggested here possesses narrower boundaries compared to usual LCA studies of electric cars. Also, it is restricted to carbon footprint quantification. The quantification of other impact categories like e.g. the mineral resource depletion (Helmers et al. 2015) can lead to adverse results. An electric car contains more high-quality metals like copper (Cu) compared to an ICEV; however, the Cu content of BEV and ICE is within the same order of magnitude (Angerer et al. 2009). In addition, the rapidly increasing electronic complexity of ICEV is believed to double the Cu content of new ICEV between 2006 and 2026 (Angerer et al. 2009). This is also true for other precious metals. Concerning lithium, it will be an essential battery component until 2030 but not necessarily beyond (Helmers 2015). In addition, metal production is responsible for less than roughly 15 % of the carbon footprint within the whole life cycle of an electric SMART (Helmers and Marx 2012) including production expenses even under the assumption of energy production by wind mills.

Table 4 Total GHG emissions of BEV and ICE vehicles with a Hybrid LCA+WTW method

WTW vehicles	Hybrid method: WTW emissions + battery footprint [g CO_2eq/km]	GHG saving of BEV [%]	Difference to "WTW only" method [%]
Battery electric vehicle	96.6	–	–
ICE gasoline (neat)	178	46 %	−10 %
ICE diesel (neat)	145	33 %	−13 %
ICE diesel with 7 % biodiesel (rapeseed)	139	31 %	−13 %

4 Conclusions

The well-to-wheel (WTW) methodology is a simplified LCA based approach useful for quantifying the energy content and GHG emissions, described as global warming potential (GWP), of fuels and powertrains in operation.

This can be considered a narrow point of view in an LCA perspective, but often, policy makers need to take decisions using only this specific subset of impact categories and limited life cycle stages. Therefore, in this article, an attempt was made to try to identify and assess the differences between

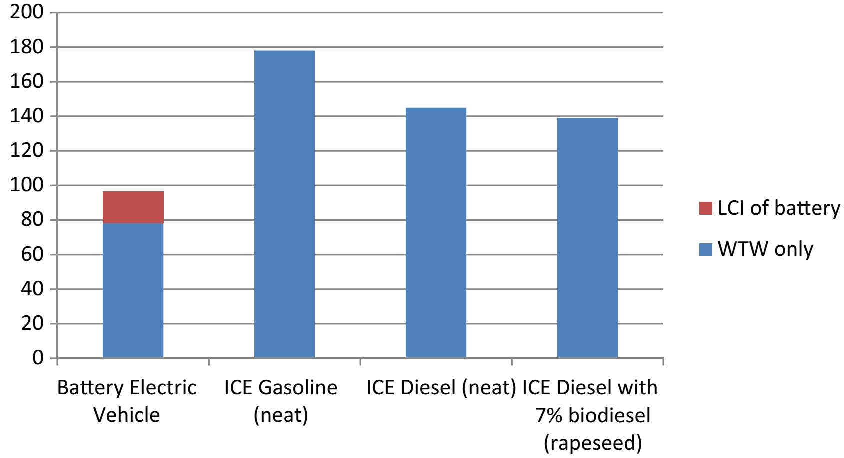

Fig. 5 GHG emissions from BEV and ICE vehicles (2009 data): difference between the "WTW Only" and the "Hybrid WTW+LCA" methods. LCI of battery: life cycle impact

WTW and LCA, and propose a way to reduce the numerical gap between LCA and WTW results.

Firstly, the GHG content of the electrical energy was analysed, giving the main contribution to the carbon intensity due to the use of a battery electric vehicle (BEV). In order to allow a better comparison between WTW and LCA results, the method for calculating the GHG intensity of the EU27 electricity mix for year 2009 in JEC WTW-4 (JEC 2014b) was described. By comparing the GHG intensity of the EU27 electricity mix by using both the WTW and the LCA methodologies, it is possible to see that these methodologies produce almost the same numerical results. Consequently, it is possible to state that for the specific application of the EU electricity mix in year 2009, the WTW method is a very good approximation of the LCA approach.

Secondly, it was described how in the WTW-4 study (JEC 2014a, b, c), the GHG intensity of the electric mix is combined with the electric consumption of a BEV to calculate the GHG emissions of an electric car (in CO_2eq/km), and the level of GHG saving was shown, according to WTW, while comparing the use of a BEV with a conventional internal combustion engine (ICE) vehicle burning fossil fuel.

Next, the scientific literature was investigated in order to find similar LCA data describing the GWP of electric vehicles, identifying in the manufacturing phase of the BEV the main contribution to the differences between WTW-4 and LCA studies. Specifically, the main and the most definite source of CO_2 emissions arises during the manufacturing of the battery pack.

In order to reduce the gap between WTW-4 and LCA studies on electric vehicles, while still allowing WTW users to keep the main advantages of the WTW method, but also having datasets more comparable with LCA results, a simple hybrid WTW+LCA methodology was proposed, keeping the main WTW assumptions but adding to the WTW emission-specific LCA data. The most relevant LCA data was identified as those which described the emissions occurring during the production stage of the battery pack of the BEVs.

According to this new hybrid method, the GHG savings associated with the use of BEVs instead of ICE vehicles are 13–10 % lower. According to the "pure" WTW-4 data set, a 44–56 % GHG saving during BEV operation was found; however with the hybrid WTW+LCA method, the savings are reduced to values ranging from 31 to 46 %.

Relying on similar viewpoints and homogenous data sets is important both for policy makers, using mainly WTW methodology, and for the scientific community, who are more focused on LCA methodology (Jungmeier et al. 2014). The authors hope this paper can help reduce the gap between the WTW and LCA approaches, stimulating the debate and contributing to the creation of a consistent and modular WTW-LCA data set.

This bridging action will be more and more necessary in the future, when a larger share of renewable energy sources feeding the electric grid will make the impact of the GHG emissions due to the production of EVs not negligible, compared to the GHG emissions of the electric energy mix, as it is now.

Finally, the authors would like to propose this methodology for an extension of the established WTW method also for other drivetrain technologies, such as fuel cells, which are intrinsically different from the ICE vehicles.

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