ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.2857

COMPARISON OF THE ENVIRONMENTAL IMPACTS OF A PLUG-IN HYBRID AND A FULL ELECTRIC CAR USING LIFE CYCLE ASSESSMENT

Artúr Szilágyi, Ákos Bereczky

Budapest University of Technology and Economics, Department of Energy Engineering
Műegyetem Rkp. 3, 1111 Budapest, Hungary
tel.: +36 30 48 20 600, fax: +36 30 9661298
e-mail: szilagyi@energia.bme.hu, bereczky@energia.bme.hu

Abstract

Full electric (FEV) and plug-in hybrid (PHEV) vehicles are promising, forward-looking technologies to reduce greenhouse gas (GHG) emissions and other pollution related to road transport. The powertrain of a FEV is composed of a battery, control electronics and the electric motors. A PHEV has much lower battery capacity but it contains an extra internal combustion engine and gearbox. Many argue that FEVs are more energy-efficient than internal combustion engines. However, this energy needs to be stored in heavy, large-capacity battery packs that require plenty of energy and resources to produce as well as highly polluting rare earth elements mining. In this article, an environmental comparison of FEVs and PHEVs is shown using life cycle assessment (LCA). To make the comparison realistic, two models similar in size and power have been selected: Volkswagen E-Golf FEV and Volkswagen GTE PHEV.

Results show that the production of FEVs need more energy and it means more burden on the environment however during the use phase it causes less emissions. Since the local electricity production mix and, in case of PHEVs, the user behaviour highly affects the results, three different countries (Hungary, Poland and Norway) and two different use types are considered. The quantified environmental footprints as well as the break-even distances are presented. Sensitivity of the results towards the assumed conditions during the whole design lifetime of the vehicles is discussed.

Keywords: *full electric vehicle, plug-in hybrid electric vehicle, life-cycle assessment*

1. Introduction

Transport is responsible for a large share of pollution and fossil fuel consumption, thus the world is increasingly looking at greener alternatives. Electric and hybrid vehicles rise as a promising, forward-looking technology to power vehicles that reduce greenhouse gas (GHG) emissions as well as other environmental impacts of road transport.

Both type of vehicle has a battery, control electronics and electric motor, but in the fully electric vehicle (FEV) is powered only by it while hybrid vehicles also have an internal combustion engine, its gearbox and additional fuel supply. Conversely, battery capacity of hybrid cars is lower.

Many argue that electric drives are more energy-efficient than internal combustion engines, however, in case of FEVs, energy needs to be stored in heavy, large capacity battery packs that require plenty of energy, long deliveries and rare metals to manufacture, the mining of which is a highly polluting industry. Thus, the question arises: which is a better solution from an environmental viewpoint. In this article, environmental impacts of electric and hybrid vehicles are compared using life cycle assessment (LCA).

2. Materials and methods

Life cycle assessment (LCA) – also known as life cycle analysis – is the assessment of the potential effects on the environment during a lifetime of a product, process, or service. The life cycle of a product is referred to as all the processes from raw material extraction, mining through manufacturing of the product to the use and end-of-life. To determine which technology has bigger impact on the environment, we used life cycle assessment (LCA) with the open-source openLCA software and ecoinvent as a background database. Functional unit was 1 km distance covered averaged over the 150 000 km assumed total mileage for both cars. To address uncertainty arising from the variations of regional electricity mixes, a scenario analysis has been set up for four different countries.

To make a fair comparison, two models similar in size and power have been selected: the full-electric Volkswagen (VW) E-Golf and the plug-in hybrid Volkswagen GTE. Both vehicles are based on the Volkswagen's versatile "MQB" modular design construction platform making it easier to focus only on the differences of the powertrains. All the rest of the components (e.g. car body. chassis, wheels, suspension, steering etc.) are considered the same, and thus left out of the analysis.

In the case of VW E-Golf, the high capacity battery has been placed on the floor of the vehicle due to the benefits of the MQB platform. Although this vehicle received a larger battery pack in 2017, we used a pre-2017 model. [1]

The VW GTE is a plug-in hybrid, so the petrol drive and the electric drive chain are present together. It should be noted that the goal of the manufacturer here was to make a more powerful, sporty car. [1] The differences between the two vehicles are illustrated in Tab. 1.

Tab. 1. Properties of selected vehicles [1, 2]

	VW E-Golf	**VW Golf GTE**
Weight [kg]	1510	1520
Battery capacity [kWh]	24.2	8.8
Battery weight [kg]	318	120
Consumption [/100 km]	17.9 kWh	3.4l + 8.8 kWh
Power [kW]	100	112 gasoline + 76 electric

3. Life cycle inventory (LCI)

As it was mentioned above, all components were assumed the same for the two vehicles and omitted from the analysis except the powertrains. The life cycle of the powertrains were separated to four main stages: raw materials & manufacturing, transport, use phase and waste management.

3.1 Raw materials & manufacturing

Differences in environmental impacts of the production phase arise from the differences listed in Tab. 1. Since the electric output power of the two makes are very similar, it is assumed that the electric motor and power electronics of the two vehicles are the same, and the differences between them was neglected.

This means that, we reduced our investigations to differences in the batteries of the vehicles and the components of the internal combustion engine of the hybrid vehicle, that is, its engine, exhaust, catalytic converter, petrol tank, and gearbox.

3.2 Battery pack

The same type of nickel-cobalt-manganese batteries are used in both vehicles [3]. Since the structure and chemistry is the same and the background database contains the flows per unit mass, environmental impacts are directly proportional to the weight of the battery pack, which is different for the two vehicles. Battery manufacturing is a complex, multi-component process. Battery cells are made up of five main components: anode, cathode, electrolyte, separator, and cell packing. The inventory and the matching ecoinvent processes are adapted from [4] without any modification.

3.3 Internal combustion engine (ICE) and components

The inventory for the ICE and its components are compiled from several sources as well as using expert estimates [5-8] as seen in Tab. 2.

Tab. 2. Life cycle inventory for ICE chain drive

Components	[kg]
Engine	125.6
Steel and Ferrous alloys	79.8
Light alloys	24.5
Iron alloys	2.7
Polymers	10.6
Other materials	1.4
Liquids and auxiliary materials	6.6
Exhaust	40
Steel and Ferrous alloys	34
Light alloys	5.6
Polymers	0.34
Catalyst	4
Metal Housing	3.1
Ceramic Structure	0.9
Catalysts	2.43 g
Palladium	1.53 g
Platinum	0.63 g
Rhodium	0.27 g
Bent tank	14
Steel and ferro alloys	3.5
Polymers	10.5
Exchange	93
Steel and ferrous alloys	79.05
Light alloys	10.69
Polymers	2.8
Ceramic	0.46

3.4. Transport

Transport of materials in a globalised supply chain might have serious effects on the overall environmental performance. It is assumed that Volkswagen is supplied by a Japanese manufacturer of battery cells for the battery assembly in Germany. ICE parts are considered in-house products for VW thus involving negligible transport. The aggregated transport volumes for the vehicles of the parts can be seen in Tab. 3.

Tab. 3. Transport volumes

	Sea [t km]	Rail [t km]	Road [t km]
PHEV	3310	186	90.2
FEV	8780	347	166

3.5. Use

Using vehicles can result in pollution in several ways. The most obvious part is the consumption of energy sources in the form of electricity and gasoline. Additionally, wear out of some parts can be significant as well (for example in particle emissions) although the list of these parts is short, and since there is little difference between the two vehicles in terms of tire and brake usage as the weight of the vehicle and output power is almost identical. In addition, their electric drive chains are similar, so regenerative braking saves brake discs and brake pads in both vehicles. [1] Consequently, differences in pollution during use are mainly due to energy carriers. The environmental impacts caused by electricity generation and supply and by the production and combustion (well-to-wheel) impacts of petrol need to be compared in the proportions of consumption during the assumed lifetime mileage of 150 000 km.

FEV operates exclusively with electric power while PHEV uses both electricity and gasoline as a fuel. The consumption of vehicles is detailed in Tab. 1. It’s important to note that the FEV's official factory consumption data was accepted as realistic while for the PHEV several sources mentioned that consumption far exceeded the factory value. Thus, a more realistic figure of 3.4 litres of gasoline per 100 km has been assumed for the latter in addition to the 8.8 kWh electricity [2] [9]. Direct ICE emissions were extrapolated using the official fuel consumption of a 1.4 litre petrol engine, resulting in 80.66 g CO_2e/km and 27 mgNO_x/km [10]. A density of 0.75 kg / litre was used for gasoline in the calculations [11]. In addition, the PHEV needs lubricating oil for the ICE, which was assumed to be 10 litres for 150,000 km.

As a baseline scenario, the Hungarian low-voltage electricity consumption mix was used for charging the batteries.

The list of wear parts was compiled using expert estimates (Tab. 4).

Tab. 4. List of wear parts

	weight [kg]
Timing belt	0.25
steel	0.1
EPDM	0.15
Guide and tension pulleys	
steel	1
water pump	1.5
aluminum	1.3
plastic	0.214

After the use phase, the cars become waste and some of the materials can recovered from the vehicles. Since the waste management of cars is well established in most countries it can be safely said that most of metal content (aluminum, copper and steel) of the ICE chain drive are recycled so we assumed 75% recycling rate. Material recovery consumes 62 kWh of electricity. Battery recycling is much more energy-intensive process, 0.9 kWh of energy is needed to process every kg of battery. The share of recyclable materials was considerably lower than in the case ICE, 15%, of which recyclable from aluminum, steel, copper and polypropylene [4]. This smaller re-usability is due to the design of the battery [4]. In E-Golf, only the battery should be reused, while for the Golf GTE, the engine and battery should also be recycled. Recycled materials were assumed to replace virgin raw materials for the manufacturing process (closed-loop recycling).

4. Results

Aggregated emissions from the life cycle of the two systems were characterized using life-cycle impact assessment methods recommended by the ILCD (Fig. 1) [12]. Climate change impacts are 21 t CO_2e and 25 t CO_2e for the FEV and PHEV, respectively for 150 000 km design mileage.

Clearly, the bigger battery capacity means a bigger share of production related environmental costs in case of the FEV compared to PHEV whereas in the life cycle of the latter, the use phase is more important.

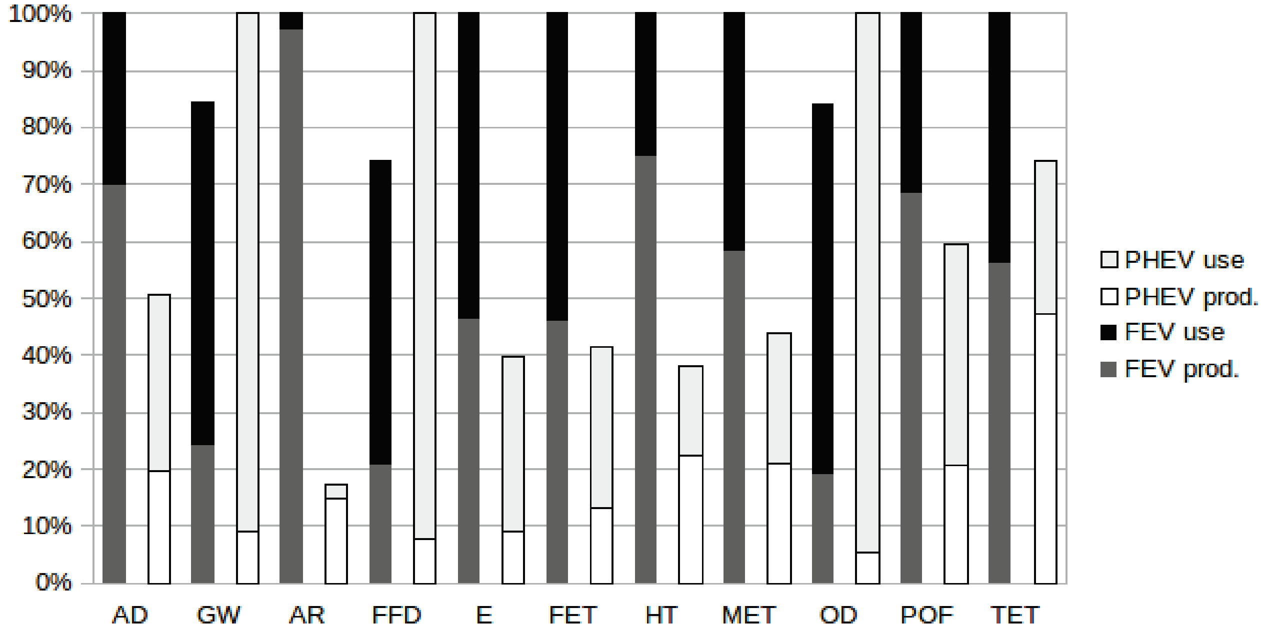

Fig. 1. Life-cycle impacts of the two systems compared (prod.: production, AD: Acidification, GW Global Warming, AR: Abiotic Resources, FFD: Fossil Fuel Depletion, E: Eutrophication FET: Freshwater Ecotoxicity, HT: Human Toxicity, MET: Marine Ecotoxicity, OD: Ozone Depletion POF: Photochemical Oxidant Formation, TET: Terrestrial Ecotoxicity)

More importantly, using FEVs results only in a slight reduction of climate change impacts, even with a relatively low-carbon electricity mix of Hungary (around 50% nuclear, 15% renewables). However, the higher production related impacts of batteries means higher impacts of FEV in nearly all other impact categories, even in photochemical smog formation where the superiority of FEVs almost seems common sense. Most probably this is due to the fact that many components of the battery is made in middle-income Eastern-Asian countries were environmental regulation are not as stringent as in Europe.

5. Discussion

5.1 Uncertainty and sensitivity of the results

Background data: some of the data is averaged over regions or temporal timeframes and it brings some uncertainty to the results. For example, production of fuel in different countries is averaged; however, the heat and electricity needed for chemical processes and fuel composition may vary from country to country.

Maturity of technologies: battery production is a novel technology and it is likely to become more energy-efficient in the foreseeable future and thus will be better off for GHG emissions than a hybrid vehicle with lower production CO_2 emissions that cannot be improved significantly.

User behaviour: Another source of uncertainty is the user behaviour in case of PHEV: if the vehicle is charged regularly and used, only for short distances (for example urban commuting) the ICE operates only in a fraction of the total driving period. However if the user does not charge the battery, ICE consumes 5.1 litres of gasoline per hundred kilometres according to factory data, which in reality can be up to 6 litres considerably increasing the PHEV’s GHG emissions.

Electricity mix: the regional mix of electricity might have a huge impact on the results. To address this issue a “break-even distance” is calculated in relation to the GHG emission factor. GHG emission factor is defined as the quantity of GHGs emitted per 1 kWh of electricity consumed during its lifecycle. For example, it is 47, 407 and 1168 gCO_2e/kWh in the case of Sweden, Hungary and Poland respectively [13]. More country specific emission factors can be found in [13]. The break-even distance is defined as the average mileage necessary for the FEV to offset its higher production related impacts with its lower emissions during the use phase compared to the PHEV.

Obviously, the "greener" the electricity mix, the shorter the break-even distance (Fig. 2).

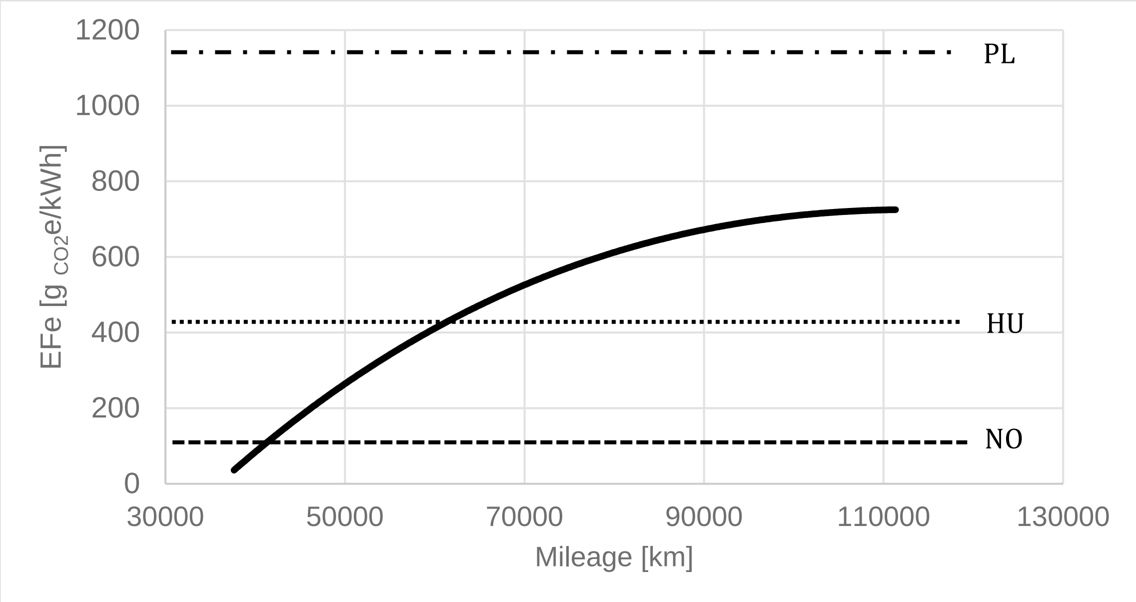

Fig. 2. Calculated brake-even mileages in the function of electricity mix (EFe: GHG emissions per unit of electricity consumed)

The GHG emission reduction benefits of using the FEVs however drop to zero above cca. 700 g CO_2e/kWh carbon intensity of electricity. The results also show that extending the use phase of the FEV's to more than the design lifetime of 150 000 km comes with significant environmental benefits.

References

[1] http://www.greencarcongress.com/2014/03/20140313-golf.html, accessed: 09.05.2018.

[2] https://www.autonavigator.hu/cikkek/fogyaszthat-15-litert-egy-golf-vw-golf-gte-teszt/, accessed: 09/05/2018

[3] https://pushevs.com/2016/09/13/volkswagens-strategy-for-batteries/, accessed: 2018.05.09.

[4] Ellingsen, L. A.-W., Majeau-Bettez, G., Singh, B., Srivastava, A. K., Valøen, L. O., Strømman, A. H., *Life cycle assessment of a lithium-ion battery vehicle pack*, Supporting Information, Journal of Industrial Ecology, 2013.

[5] Arlt, N., *Korrosions-und hitzebeständige Stahle in Abgassystemen*, CTI Exhaust Materials Forum, Frankfurt, Germany 2007.

[6] ASM, Metals Handbook, ASM International, Materials Park, OH, USA 2001.

[7] https://www.dieselnet.com/tech/diesel_exh_mat.php, accessed: 09.05.2018.

[8] https://fabione63.it/doc/Dual-clutch%20gearbox%20DSG.pdf – VW gearboxes LCA report, accessed: 09.05.2018/

[9] https://totalcar.hu/tesztek/2016/03/16/volkswagen_golf_gte_2016/, accessed: 09.05.2018.

[10] https://www.volkswagen.hu/media/Kwc_Basic_DownloadTag_Component/23547_brochures-56532-child-download-downloadTag/default/531f45e8/1495807561/golf-technikai-adatok.pdf, accessed: 09.05.2018.

[11] http://www.nextgreencar.com/view-car/63660/vw-golf-1.4-tsi-s-125ps-bmt-dsg-petrol-semi-

automatic-7-speed/, accessed: 09.05.2018.
[12] European Commission, Joint Research Centre, Institute for Environment and Sustainability. Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods. Database and Supporting Information, First edition, EUR 25167, Publications Office of the European Union, Luxembourg 2012.
[13] Alberto Moro, Laura Lonza, Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles, Transportation Research Part D: Transport and Environment, ISSN 1361-9209, https://doi.org/10.1016/j.trd.2017.07.012, 2017.
[14] http://www.vwscirocco.es/bricos/manuales/tsi_background_report.pdf, VW engines LCA report, accessed: 09.05.2018.

Manuscript received 20 March 2018; approved for printing 29 June 2018