Well-to-wheel analysis of GHG emissions in electric vehicles-critical review

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ABSTRACT

The growing environmental concern has led to the search for new energy and powertrain systems. Electric vehicles (EVs) are emerging as a promising and sustainable alternative. EVs can be classified as Hybrid Electric Vehicles (HEV), Battery Electric Vehicles (BEVs), Plug-In Hybrid Electric Vehicles (PHEVs) and Fuel Cell Electric Vehicles (FCEVs).

The Well-to-Wheel (WTW) analysis assesses the total primary energy consumed by the vehicle for each kWh of energy supplied to the vehicle's wheels, comprising all stages covered by the well-to-tank conversion path and, later, by the conversion of energy on board from the tank to the wheels.

This study intends to carry out an analysis under the WTW perspective comparing EVs to conventional vehicles, under the viewpoint of GHG (greenhouse gas) emissions. A search will be carried out in the Scopus database, to select articles, between the years 2002 and 2020 (08/may), with the keywords: well-to-wheel and greenhouse gas emissions and electric vehicle.

The electricity generation mix, the source of hydrogen production, the technologies for producing electricity or hydrogen, the losses during transmission and distribution of energy, the battery technologies, the attitude of ecological driving and the autonomy of the vehicle are all important factors that have great influence on GHG emissions. Only the introduction of electric vehicles in countries does not guarantee a reduction in GHG, being necessary to analyze the entire life cycle.

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INTRODUCTION

Nowadays, much has been discussed about greenhouse gas (GHG) emissions and their impact on the environment. The emitted gases that are the main causers of greenhouse effect are carbon dioxide, methane, nitrous oxide and fluorinated gases [1]. In 2018, in the United States the main GHG emitted was carbon dioxide (81% of emissions) [2]. Globally, the transport sector represented 15% of GHG emissions in 2013 [3]. In Canada, in 2017 the transport sector accounted for 28% of GHG emissions [4]. In 2016, the transport sector in China represented 1,83% of global GHG emissions, in the USA 3,71%, EU 1,71%, and in Brazil 0,43% [5]. Among the modes that contribute the most to carbon dioxide emissions, light cars lead with 45% of the volume emitted globally [6].

Electric vehicles are considered the most promising alternative to internal combustion engine vehicles (ICEVs) for a cleaner transport sector [7], contributing to reduce GHG emissions [8]. Electric vehicles are divided into Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV) and Fuel Cell Electric Vehicles (FCEV). An existing type of HEV is the Plug-in, which's battery can be recharged directly through an outlet.

GHG emissions can be assessed using a WTW (well-to-wheel) analysis. The WTW analysis can be divided into two stages, from well-to-pump (WTP) and pump-to-wheels (PTW) [9]. A WTW analysis, Figure 1, assesses GHG emissions caused by all the processes of vehicles fuel life cycle [10]. The WTP stage includes processes such as raw material recovery, fuel production, fuel storage and distribution to filling stations [9]. The PTW stage includes fuel consumption during vehicle operation [11]. Liu et al. [9] carried out an analysis of energy use and WTW emissions, in which an FCEV (Toyota Mirai) was compared to a conventional gasoline-powered ICEV (Mazda 3). The authors concluded that, even being powered by hydrogen from a fossil-based production path (via steam methane reform from natural gas), 5% to 33% less fossil energy is used in WTW, and it produces 15 to 45% less greenhouse gases from WTW in comparison to the conventional gasoline ICEV.

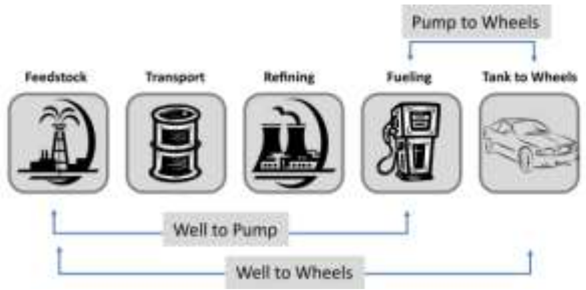

Figure 1. WTW fuel pathway. Adapted from [12].

Kromer and Heywood [13] quantified the potential of electric propulsion systems to reduce oil use and GHG emissions in the US light vehicle fleet by 2030. The propulsion systems under consideration include gasoline HEVs, plug-in hybrid vehicles (PHEVs), fuel cell hybrid vehicles (FCEVs) and BEVs. The results showed that continued reliance on fossil fuels without effective capture and sequestration of carbon for the production of electricity and hydrogen would restrict GHG and energy emission reductions to about 60% below spark-ignition technology. Petrauskien et al. [14] presented a WTW analysis for conventional and electric vehicles, with different scenarios of electricity mix, which are forecasts for the years 2015 and 2050 in Lithuania. In terms of climate change, the results show that BEVs with the electricity mix of 2015 generate 26 and 47% more GHG emissions than those of ICEVs fueled by gasoline and diesel.

In international bibliography there are some other studies that address WTW analysis of GHG emissions, comparing the different existing types of powertrains. Therefore, better knowing these data and interpreting them is important to have decision support information for researchers, as well as for political and business decision makers. As the main justification for the increase in the number of electric vehicles is their potential to reduce GHG emissions, then studies that prove this advantage are very important. The WTW analysis has been an effective tool in the assessment of energy use and the impact of GHG emissions from alternative options of powertrain systems [15].

In this study, an analysis was carried out under the WTW perspective comparing EVs with conventional vehicles, from the point of view of GHG emissions. The search was performed in the Scopus database using the following keywords: well-to-wheel; greenhouse gas emissions; electric vehicles. The research was performed considering the period from 2002 to 2020 (May this year), in title, abstract and keywords. The selected types of documents were articles, conference papers and reviews.

LITERATURE REVIEW

This section presents a bibliometric analysis, and also a well-to-wheel analysis.

BIBLIOMETRIC ANALYSIS

The search resulted in 166 documents, having articles (94 documents, 56,65%), conference papers (62 documents, 37,35%) and reviews (10 documents, 6%). In an analysis of documents by affiliation, the following institutions stand out: Argonne National Laboratory (21 documents), Tsinghua University (16 documents), Virginia Polytechnic Institute And State University (15 documents), United States Department Of Energy (6 documents), Vrije Universiteit Brussel (5 documents).

The countries with the most documents are: United States (85 papers), China (25 papers), Canada (11 papers), Germany (9 papers), Italy (7 papers), United Kingdom (7 papers). The main sources are: SAE Technical Papers (22 papers), Applied Energy (11 papers), Transportation Research Part D Transport And Environment (11 papers), Energy (8 papers), International Journal Of Hydrogen Energy (7 papers). The keywords with the most occurrences in the articles were: greenhouse gases (143 occurrences), gas emissions (109 occurrences), electric vehicles (59 occurrences).

When analyzing the documents by subject area, the following results are obtained: Engineering (31,6%), Environmental Science (26,4%), Energy (21,9%), Chemistry (3,3%), Physics and Astronomy (2,1%), others (14,7%). The authors with the most documents are: Wang, M. (15 papers); Nelson D.J. (15 papers); Elgowainy, A. (8 papers); King, J. (8 papers); Wu, Y. (7 papers). The most cited articles are: Aprotic and aqueous LI-O_2 batteries [16] (617 citations); Greater focus needed on methane leakage from natural gas infrastructure [17] (353 citations); Fuel cell and battery electric vehicles compared [18] (318 citations); Environmental impacts of hybrid and electric vehicles-a review [19] (239 citations); A sustainability assessment of electric vehicles as a personal mobility system [20] (152 citations).

WELL-TO-WHEEL ANALYSIS

The study of Thomas [18] analyzed some scenarios with different powertrain systems, based on the years from 2010 to 2020 in the USA. On average, 52% of the electricity used came from coal and had a 35% efficiency in the electricity grid. The data to find GHG emissions take into account a WTW analysis. The results show that a lithium-ion battery EV with a range of more than 430 km would generate more GHG emissions than a comparable gasoline car. The gasoline-powered ICE version of the analyzed vehicle produces about 550 g/mile of CO_2 equivalent emissions, so that FCEV powered by hydrogen produced from natural gas would reduce GHG emissions by approximately 47% in comparison to gasoline cars.

Meinrenken and Lackner [21] commented that plug-in and hybrid vehicles offer possible reductions in GHG emissions, depending on the intensity of the carbon grid, the range and, therefore, the battery emissions, life cycle, vehicle weight, and travel patterns. The potential of plug-in hybrid electric vehicles (PHEV) to reduce greenhouse gas emissions depends largely on the use of the vehicle and the source of the electricity [22]. More regular driving, less long-distance travel and recharging during the day increases the share of electric steering and reduces conventional fuel consumption.

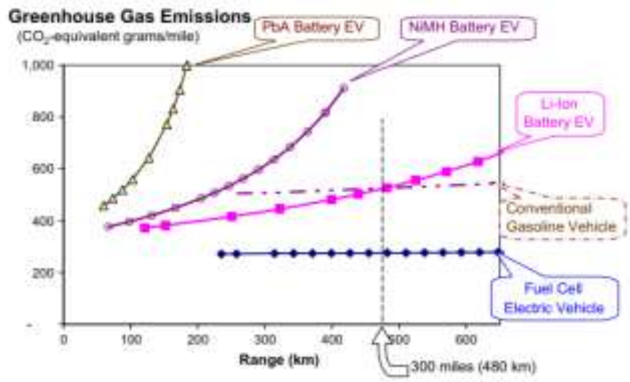

Figure 2. WTW GHG due to the range of the vehicle for the United States. Adapted from [18].

Woo et al. [23] analyzed GHG emissions associated with electric vehicles in 70 countries worldwide, in relation to their domestic electricity generation mix. The results show that GHG emissions associated to the BEVs that use electricity generated from fossil fuels, such as coal, natural gas and oil, considerably exceed the amount of GHG emitted in the cases where electricity is generated by other energy sources. GHG emissions from ICEVs (gasoline and also diesel) were higher than those from BEVs (which use electricity generated by natural gas, nuclear energy and renewable energy sources) in the four vehicle categories. The electricity of BEVs, being generated from natural gas, nuclear energy or renewable energy sources, leads them to having less negative impacts on the environment than ICEVs. BEVs that use electricity generated from coal or oil have always had higher GHG emissions than diesel ICEVs. BEVs using coal-generated electricity in the compact and subcompact car categories and BEVs using oil-generated electricity in the subcompact car category presented higher emissions than their corresponding gasoline ICEVs.

Shen et al. [24] conducted a well-to-wheel life cycle analysis on total energy consumption and GHG emissions from alternative fuels for 2010 as the base year and projected for 2020 in China. Vehicle electrification using HEV, PHEV and BEV technologies offers a great perspective on energy consumption and reduced GHG emissions. However, the latter is guaranteed only when the electricity used by PHEVs and BEVs is generated from zero or low carbon sources, which means that CCS (carbon capture and storage) is a necessity if coal or natural gas is used as feedstock. CCS also becomes necessary if fossil fuels are used as source for hydrogen.

Wu and Zhang [25] studied different types of gasoline ICEVs and electric vehicles, comparing their effects on the environment, in developed countries (Germany, France, Japan, USA) and in developing countries (China, Russia, India, Brazil), with the WTW method. The results show that, compared to gasoline-powered ICEVs, electric vehicles have a significant effect in reducing CO_2 emissions. The best CO_2 emissions reduction effects due to the use of PHEVs and BEVs are found in France and Brazil. In these two countries, replacing a gasoline ICEV for a year with a PHEV leads to a reduction in CO_2 emissions of 2365 and 2356 kg, respectively (more than twice as much as when using a HEV). Replacing a gasoline-powered ICEV for a year with a BEV reduces CO_2 emissions by 2834 and 2823 kg, respectively (about 2,8 times the reduction effect in comparison to the use of a HEV).

Yazdanie et al. [26] provided a comprehensive comparison of WTW energy demand, WTW GHG emissions, and the costs of conventional ICE transmission groups and electric vehicles. Energy carriers and battery production are the main contributors to WTW energy demand, GHG emissions and costs. WTW emission reductions depend more on the energy carriers' production path than on the power train. GHG WTW emissions are reduced by at least 50% compared to gasoline-powered ICEVs in all transmission groups when using an energy carrier based on a renewable energy source, including biomass and solar energy. Vehicles based on natural gas and biogas (including ICEV, HEV, PHEV and FCEV using steam methane reform and partial oxidation) also produce notable reductions in WTW energy demand. The PEVs and FCEVs that use electricity to produce hydrogen are sensitive to changes in the electricity mix, particularly in the case of FCEVs, where additional losses occur due to the conversion of electricity during electrolysis.

Kamiya et al. [27] studied the intensity of short-term (2015) and long-term (2050) WTW GHG emissions of PEVs in three regions with very different power grid profiles: the Canadian provinces of British Columbia, Alberta and Ontario. The results show that PEVs offer substantial benefits in GHG emissions compared to conventional vehicles in all scenarios explored. In the short term (2015), PEVs reduced greenhouse gases in range from 34% to 98%, varying according to the network's regional mix. In the long term (2050), the PEV GHG intensity is from 36% to 74% lower than the 2015 levels.

Moro and Lonza [28] provided WTW calculations, based on 2013 statistical data, for the carbon intensity of the European electric mix. The data show that the use of electric vehicles instead of gasoline vehicles can save (about 60%) GHG in all or most EU Member States, depending on the estimated consumption of electric vehicles. Compared to diesel, the electric vehicles present average GHG savings of about 50%, and no savings in some EU Member States.

Li et al. [29] reported the results of WTW analyzes for BEVs and FCEVs for different energy resource and technology pathways in China in terms of fossil energy use, total energy use and GHG emissions. Energy types include coal, natural gas, renewable energy and nuclear energy resources. When considering the cabin heating load on vehicles, FCEVs that use natural gas as an energy source outperformed all BEVs in terms of total energy use and GHG emissions. FCEVs that adopt new energy-based paths can achieve the same WTW efficiencies as BEVs, and those efficiencies can be even higher if the hydrogen used by FCEVs is produced through solid oxide electrolyzer cells (SOEC), solar thermochemical systems or nuclear SOEC systems.

Yoo et al. [11] provided a WTW GHG analysis for various H_2 production pathways for FCEVs in Korea: naphtha cracking, steam methane reform, electrolysis and coke oven gas purification. WTW's greenhouse gas emissions in FCEV are calculated as 32571 to 249332 g-CO_2 eq./GJ or 50,7 to 388,0 g-CO_2 eq./km, depending on the H_2 production pathway. Electrolysis with the Korean grid mix (on site) has the highest GHG emissions due to the high emission factor in the power generation process.

Faria et al [30] conducted a detailed analysis of the electricity mix, which was based on the contribution of each type of primary energy source and its variation over a year. Three mixtures were considered, with different intensities of GHG in the life cycle: the first one based mainly on fossil sources, a second one with a great contribution from nuclear energy, and a third with a significant share of renewable energy sources. Conventional vehicle technology is represented by gasoline and diesel ICEVs, while electric technology is represented by PHEVs and BEVs. The results show that a mix with a large contribution from renewable energy sources does not always translate directly into low GHG emissions for electric vehicles, due to the high variability of these sources. The driving profile in different scenarios was also analyzed, demonstrating that an aggressive style can increase energy consumption by 47%. The tests have also shown that the use of climate control can increase energy consumption by between 24 and 60%. Compared to other technologies, electric vehicles can be more environmentally and economically sustainable; however, three main factors are needed for it: improvement in battery technology, an eco-friendly driven attitude and an ecological electricity mix.

Ramachandran and Stimming [31] compared the use of alternative fuels: electricity, hydrogen and bioethanol, in combination with the technologies of BEVs and FCEV, based on their overall efficiency and on the GHG emissions involved in converting the primary energy source to the actual energy needed, and through an WTW analysis. The energy source for electricity production plays an important role in determining the overall efficiency and GHG emissions of a BEV. Therefore, the electricity production mix from Germany (60% fossil fuel energy), France (76% nuclear energy), Sweden and Austria (60 and 76% renewable energy, respectively), the European Union mix (48% fossil fuel energy) and the United States of America (68% fossil fuel energy) are considered for the BEV analysis. The results of this study present that a BEV powered by a mix of electricity production mainly derived from renewable sources, direct ethanol fuel cell based on renewable energy and bioethanol, offers the best solution in terms of GHG emissions, efficiency and dependence on fossil fuels. Bioethanol as a fuel has the additional advantage of being readily implemented in ICEVs, followed by advances through FCEVs based on reformers and electric vehicles with direct ethanol fuel cell. Regarding BEVs, in countries with a high proportion of nuclear or renewable energy in their generation mix, BEVs are significantly more environmentally friendly than ICEVs [32]. Although the tank-to-wheel electricity consumption in electric vehicles is the same for all countries, the well-to-wheel consumption is different in each country, depending on the composition and proportion of primary sources for electricity production, the electricity generation technology used, and the distribution efficiency in the electrical network until the final customer [33].

Qiao et al. [34] analyzed the GHG emissions of the Cradle-to-Gate (CTG), Well-to-Wheel (WTW) and Grave-to-Cradle (GTC) phases for different vehicles at different times, based on the compact A0-A sedan model sold in China. The results indicate that the GHG emissions for the life cycle of an EV are about 41,0 t CO_2eq in 2015, 18% lower than those of an ICEV vehicle. This figure may decrease to just 34,1 t CO_2eq in 2020 due to the reduction in the GHG emission factor for electricity. Although the WTW phase is the largest contributor to the GHG emissions of the two vehicles, the proportions of each phase are quite different. GHG emissions in the WTW phase of an electric vehicle are decreasing rapidly, but the CTG phase will not be improved at the same pace, what can become a barrier to fully avail the environmental benefits of an electric vehicle. There are two major opportunities for reduction throughout the life cycle, beyond the development of fuel economy. One is EV recycling, which can cut by about half the GHG emissions from the CTG phase. The other is the improvement of the clean energy network that can further reduce GHG emissions from the WTW phase. Still in China, Shen et al. [35] claim that with the current heterogeneity in the electricity mix of the grid, the GHG benefits of BEVs vary dramatically according to location.

Zheng et al. [36] elaborated a new inventory of energy use and emission of the life cycle, collecting updated data, including the electricity generation mix, emission controls in the industrial and energy sectors, and the use of energy in the transportation of fuel, in order to estimate the GHG of the WTW and air pollutant emissions for BEVs and gasoline vehicles in China. The results demonstrate that an average BEV has WTW GHG emissions 35% lower than an average gasoline car. Compact and small-size vehicles generally have lower GHG and pollutant emissions than medium and large size vehicles. Compact vehicles contribute more to the absolute amount of GHG, thus they have the greatest potential for reducing emissions.

Helmers and Marx [37] reviewed and assessed the energy efficiency and environmental impact of BEVs. Literature data on energy consumption and GHG emissions by ICEV compared to BEV are underestimated by 25% for the numbers of driving cycles standardized by ICEV in relation to street conditions until 2012. The available literature data for the BEV were mainly modeled and based on a relatively heavy BEV, as well as driving conditions which do not represent the most useful field of the BEV operation. According to the authors, the small size BEVs were underrepresented in the literature data for the life-cycle assessment until 2012.

Patil et al. [15] present WTW analysis of automotive fuel consumption and greenhouse gas emissions in India. Complete Well-to-Wheel results show that diesel vehicles are the most efficient of all configurations, specifically the diesel hybrid electric vehicle. The hydrogen engine configurations are the least efficient due to the low efficiency in the hydrogen production from natural gas. The hybridization of electric vehicles substantially reduces greenhouse gas emissions of well-to-wheel, with the split hybrid configuration being the most efficient one. Electric vehicles offer no significant improvement over gasoline-powered configurations; however, a move towards renewable sources for energy generation and losses reduction throughout transmission and distribution may make it a viable option in the future. Ray et al. [38] also conducted studies for the case of India. The authors concluded that electric vehicles can be used as a means of reducing GHG emissions only after the year 2035, in the energy scenario where carbon prices have started to strongly affect energy decisions.

CONCLUSION

The present study aimed to evaluate the different types of electric powertrain systems in comparison to the traditional ones, under the point of view of GHG emissions from well-to-wheel. This study can be used as decision support for researchers as well as for political and business decision makers. The main conclusions regarding this study are summarized as follows:

1. The electricity production mix must be environmentally friendly to provide significant GHG reduction results. In some cases, BEVs, depending on the electricity mix, may emit more GHG than conventional gasoline or diesel ICEVs. However, a mix with a large contribution from renewable energy sources does not always translate directly into low GHG emissions for electric vehicles, due to the high variability of these sources (case the fossil power to be in standby to take over the generation in the case of failure from the renewable sources);

2. In the same country, depending on the location, GHG emissions can vary dramatically, because there is heterogeneity in the electricity generation mix;

3. For production technologies using fossil sources, carbon capture and storage is a possibility;

4. Losses reductions during power transmission and distribution are important in many countries to achieve better results in reducing GHG emissions. The electricity generation technologies used are also essential to contribute to the reduction of GHG;

5. Improvement is necessary in battery technology in order to achieve better results in reducing GHG. Vehicles with lower autonomy potentials show better results in reducing GHG. The increase in autonomy favors the increase in GHG emissions;

6. Attitudes with ecological direction are also important to help decrease GHG emissions;

7. Vehicle electrification using HEV, PHEV and BEV technologies offers a great prospect for the reduction of GHG emissions.

Electric vehicles still need further development on many issues in order to be widely used and provide significant emission reduction results. Only the introduction of electric vehicles in countries does not guarantee a reduction in GHG, so it is also necessary to analyze the entire life cycle.

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