Greenhouse Gas Emissions of Full Electric Mobility

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Global warming originates mainly from greenhouse gas (GHG) emissions. Among them, carbon dioxide is the most critical man-made greenhouse gas that is constantly referred to. For this reason, total greenhouse gases are measured as carbon dioxide equivalent (CO_2-eq), a unit of measurement used to standardize the effects of the various greenhouse gases on the climate. CO_2-eq is a metric used to compare the emissions of different greenhouse gases based on their global-warming potential (GWP) by converting the amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.

electric transition | road transport sub-sector | passenger vehicles | energetic scenario

1. Introduction

Global warming is becoming the main topic in the discussion tables to define the imminent future in terms of energy saving. Global warming originates mainly from greenhouse gas (GHG) emissions. Among them, carbon dioxide is the most critical man-made greenhouse gas that is constantly referred to. For this reason, total greenhouse gases are measured as carbon dioxide equivalent (CO_2-eq), a unit of measurement used to standardize the effects of the various greenhouse gases on the climate. CO_2-eq is a metric used to compare the emissions of different greenhouse gases based on their global-warming potential (GWP) by converting the amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.

In recent times, there has been discussion in Europe, and beyond of forcing the ecological transition over time by zeroing as soon as possible the CO_2 emissions allowed from vehicles. With this objective, the most immediate solution would be the transition to electric mobility at least of the current car fleet. The advantages of pure electric mobility are linked to the possibility of zeroing CO_2 emissions, and not only where the vehicles are used. Furthermore, electric vehicles are characterized by very high efficiency compared to traditional ones: this aspect is directly linked to energy saving and less maintenance, which are among the main objectives of the current ecological transition plan.

Given the above, it is worth mentioning that the annual CO_2 impact of road transport alone is 11.9% [1]; this percentage share is significant, but not so much as to justify the destruction of the automotive industry and all related industries, nor the economic and social expenditure that would result from it. Climate Watch in 2020 reports GHG emissions by sector in [1]. A total of 41.7% of GHG emissions are due to energy in buildings and energy in industry sub-sectors, of which 37% is attributable to the production of electricity. Why? Because fossil fuels produce 60% of the world's electricity [2]. The sum of coal, gas, and oil covers the production of 15,000 TWh out of the total 25,000 TWh produced in 2020.

2. Use Stage

In the overall energy assessment, focusing only on GHG emissions from the tailpipes of conventional/hybrid vehicles is simplistic and misleading. It is necessary to take into account the actual GHG emissions in the evaluation of the use phase of both thermal engine vehicles and electric vehicles. Assessing the "direct" environmental impact of the conventional vehicle during its use is simple, while it is less intuitive for a BEV.

2.1. Tailpipe Emissions for ICEVs

In this paragraph, only the average CO_2 emissions from vehicle exhausts have been considered because the focus is on the analysis of the most relevant critical issues related to energy transition. Average CO2 emissions depend on the type of vehicle and fuel for cars equipped either exclusively or even with a conventional engine. Average fuel consumption is related to CO_2 emissions. In 2021, the target value for CO_2 emissions from passenger cars was 95 g/km.

In 2019, the average CO_2 emissions of all new cars reached 122.3 gCO_2/km. Although this is below the European fleet-wide target of 130 gCO_2/km set for 2015–2019, it is well above the 2021 target of 95 gCO_2/km. HEVs could help in the process of reducing GHG emissions from engine tailpipes. It is worth noting that, in the case of PEVs, the impact of the GHG emissions emitted during the process of producing the electricity needed to charge the vehicle battery directly from the public grid is neglected. However, this approach is misleading in the overall assessment of GHG emissions, as explained in the following paragraph. The CO_2 emissions of the internal combustion engine must be added to those deriving from the production of electricity needed to recharge the PEVs. Taking this element to an extreme, CO_2 emissions from BEV use should also be reported based on European average data, at least, to remove the misconception of "zero-emission vehicles".

2.2. GHG Emissions Linked to the Energy Production System

Both PEVs and BEVs need to be charged using electricity: the average GHG emissions for recharging BEVs and PEVs should be evaluated considering the production source of the consumed electricity [3]. GHG emissions are a function of the electric energy production source and the electric energy consumption per kilometer of the vehicle (measured in kWh/km).

3. Production Stage

3.1. Life Cycle Assessment (LCA) of Vehicle Production: ICEV and BEV in Comparison

In [4], the authors provided the results of a comparative environmental assessment of a turbocharged gasoline ICEV and a lithium-ion BEV using the LCA methodology. The impact assessment results showed that BEVs significantly reduce the impact of climate change due to the absence of tailpipe emissions during operation at the point of use. The study of different grid mixes for electricity production showed that this advantage grows significantly as the share of renewable sources increases. On the other hand, the production of BEVs has a more significant environmental impact than ICEVs, mainly due to the extensive use of metals, rare earth metals, and the energy required by specific electric powertrain components, such as the high voltage battery. The other environmental impacts considered, such as acidification, human toxicity, particulate matter, photochemical ozone formation, and resource depletion, were found to be higher for BEVs than for ICEVs. Therefore, the authors stated that the evaluation of electric cars cannot be performed using a single indicator, but should be based on a more complex evaluation approach. The authors in [4] determined the break-even point for the practical environmental convenience of the electric car. The authors considered three grid mixes for electricity generation: average European, Norwegian, and Polish grid mix.

The last two grid mixes have opposite environmental profiles. The main results, reported in **Table 1**, are:

Table 1. Resume of the break-even points for the practical environmental convenience of electric car (Data source [4])—Mileage considered for LCA: 150,000 km.

LCA Results	Break-Even Point [km]	Type of Electricity Mix
Climate change	45,000	European (mean)
	30,000	Norwegian
	Never	Polish
Acidification	Never	European (mean)
	180,000	Norwegian
	Never	Polish
Photochemical ozone formation	Never	European (mean)
	130,000	Norwegian
	Never	Polish
Human toxicity	Never	Mileage-independent LC stage
Particulate matter	Never	Mileage-independent LC stage

- Climate change: the environmental convenience of the electric configuration occurs at a low mileage value (about 45,000 km) compared to the total LC distance (150,000 km). The break-even point for the Norwegian electricity grid mix decreases to around 30,000 km. At the same time, the result is the reverse when considering the Polish grid mix, as no break-even occurs.

- Acidification: the BEVs have the break-even point at around 180,000 km, a value higher than that assumed as reference LC mileage (150,000 km).

- Photochemical ozone formation shows a similar trend to acidification: effects of ICEV are preferable for any vehicle mileage, except BEVs charged by electricity produced in Norway (break-even point near the end of car life, about 130,000 km).

- Human toxicity, particulate matter, and resource depletion: no threshold mileage is detected between ICEV and BEV. The contribution of mileage-independent LC milestones is higher for the electric car for these categories. Considering that the use phase confirms this trend, the results of the ICEV are preferable from an environmental point of view.

Therefore, BEVs have the potential to reduce the impact of climate change compared to ICEVs only if the electricity consumed is produced only from non-fossil energy sources.

3.2. GHG Emissions from the Battery Production Process

According to [5], in 2020, producing 1 kWh of electricity in Europe was equivalent to the emission of 238 g of carbon dioxide into the atmosphere, deriving mainly from non-renewable sources composed of fossil fuels. According to European plans, by 2050, the goal is to produce 1 kWh of electricity with zero-carbon emission. It follows that the environmental impact of battery production is linked to the eco-compatibility of state networks, their renewable/non-renewable energy mix, and the ratio between grams of CO_2 emitted per kilowatt hour produced (gCO_2/kWh). This latter parameter is more critical in the U.S., where, in 2020, 1 kWh was worth about 383 g of CO_2, and it was worse in China, where 1 kWh was equivalent to at least 556 g of CO_2. It was not much better in South Korea: 1 kWh generates 476 g of carbon dioxide, as in Japan, which stood at 470 g (as summarized in **Table 2**). To date, Europe accounts for 1% of total battery production, compared with 60% of China, 17% for Japan, and 15% for South Korea (**Table 2**).

Table 2. Carbon dioxide emissions for producing 1 kWh of electricity and percentage of battery production in the world.

Area of the World	Carbon Dioxide Emissions for Producing 1 kWh of Electricity [gCO_2/kWh]	Percentage of Total Battery Production in the World [%]
Europe	238	1
China	556	60
South Korea	476	15
Japan	470	17

Area of the World	Carbon Dioxide Emissions for Producing 1 kWh of Electricity [gCO_2/kWh]	Percentage of Total Battery Production in the World [%]
USA	383	7

can store) y battery l burden" like the construction of a thermal or hybrid vehicle. The production of a thermal or hybrid powertrain does not generate a carbon footprint comparable to that deriving from the production of a battery for electric vehicles. The electric car becomes an advantage for the ecosystem only when its battery production's more significant carbon footprint is offset.

In [6], LCA defined the environmental impact of the battery: with 2.1 million BEVs and PEVs sold in 2019 (2.6% of global car sales), the current world stock of EVs is 7.2 million (around 1% of global car stock). Firstly, for the correct estimation of the energy impact of a battery, it is necessary to calculate its effective mass; the greater the mass of the battery, the greater the energy to be supplied for vehicle mobility.

In [6], the authors reported the most evaluated characteristics of the battery. An important parameter to evaluate the difference in effective mass between a conventional and an electric vehicle is the specific energy of the battery expressed in Wh/kg. The median value reported in [6] is 115 Wh/kg; by 2025, this value should be increased to 225 Wh/kg [7]. The global trend is to improve the characteristics of the battery, i.e., to increase its specific energy (which makes it possible to reduce its weight) and its nominal capacity (which makes it possible to increase its mileage). Computing the energy demand for battery production is not trivial. As reported in [6], the GHG emissions of the overall battery production have a median value of 120 $kgCO_2/kWh_{bc}$ (where kWh_{bc} stands for kWh of battery capacity). Therefore, producing a battery of the same capacity in Europe (currently this production is practically non-existent) would be virtually more sustainable: 2.2 tons of CO_2 (1 kWh is 238 g of CO_2), while in the U.S., the calculation would rise to 3.6 tons (where 1 kWh causes the production of 383 g of CO_2), and in Japan and South Korea, the calculation rises to 4.4 tons (1 kWh is worth about 440/446 g).

Therefore, the production of batteries is all the more polluting the "dirtier" the energy used for its production. Furthermore, since several countries have adopted the battery recycling process, it seems useful to add up the GHG emission savings by replacing the raw material and the overall GHG emissions from the recycling process. The overall average savings is 20 $kgCO_2/kWh_{bc}$ [6].

Another aspect must be considered in the cost of the environmental impact linked to the ecological transition: the effective use of the vehicle. The average battery life value reported by the manufacturers is around 8–10 years, or an average distance of 180,000 km. Automakers state that a battery must be replaced when its actual capacity drops below 70% of its rated capacity. A traditional vehicle could have a range of around 200,000 km but an effective life of over ten years. The electric battery has a life of 8–10 years regardless of the number of effective recharging processes, i.e., the battery degrades even if not used. Therefore, in the economic and ecological comparison between electric and traditional vehicles, the cost of battery replacement must be considered. For a medium/large vehicle, battery replacement could amount to 25% of the entire cost incurred for the purchase of the vehicle. Therefore, if the life expectancy of the BEVs is more than ten years, the calculated GHG emissions for battery manufacturing must be doubled to consider battery replacement.

3.3. GHG Emissions from Fuel Production and Supply Process

This paragraph shows the average value of GHG emissions relating to the production process for petrol, diesel, and hydrogen. The GHG emissions for hydrogen depend on the type of production process, as illustrated in **Table 3** (data source in [8]).

Table 3. GHG emissions for the hydrogen production process (Data source [8]).

Production Process	kg_{CO2}/kg_{H2}	LHV [MJ/kg]	g_{CO2}/MJ
Natural gas (no carbon dioxide capture)	7.05		58.75
Electrolysis of water (necessary electric energy derived from a standard electric mix)	34.68	120.00	289.00
Sulfur-iodine thermochemical cycle (S-I cycle)	10.34		86.17

In **Table 4**, GHG emissions were calculated per unit of fuel energy, represented by its lower heating value (LHV). A solution to overcome the problem related to GHG emissions deriving from the production process and supply of fossil fuels is represented by synthetic fuels, in particular e-fuels.

Table 4. GHG emissions for fossil fuels production process (Data source [9]).

Type of Fuel	kg_{CO2}/kg_{FUEL}	LHV [MJ/kg]	g_{CO2}/MJ
Gasoline	0.923	46.4	19.9
Diesel	0.999	45.6	21.9

As reported in [10], traditional energy sources make the energy supply more predictable than renewable energy resources, which have to overcome the challenge of their intermittence (there are periods when it is not possible to harvest energy), which depends on the weather conditions. Therefore, renewable sources are not suitable as a sole source of energy. It is not possible to program a sudden start-up of the traditional energy production systems (a steam power plant takes about 24 h) to deal with unexpected “holes” in the production of energy from renewable sources. The idea could be to make the two plants work together and to use any excess of energy from renewable sources in a different way. Hydrogen and synthetic fuels are chemical energy carriers; the surplus of electricity from renewable sources would produce such fuels. Using these e-fuels in existing conventional or hybrid vehicles represents an excellent opportunity to reduce GHG emissions in the short to medium term. The production of hydrogen and synthetic fuels has the potential to support the defossilization and decarbonization of the transport sector. Waste electricity occurs when renewable supply exceeds grid and end-consumer demand. Germany’s total amount of unused electricity (ghost electricity) was 3.7 TWh in 2016, out of a total electricity demand of 520 TWh per year (0.7%). Forecasts show that this energy surplus could increase to 40 TWh in 2040 (7.7% of the current energy demand). Therefore, hydrogen and synthetic fuels are a viable scenario for 2030. By capturing CO_2 from the air and combining it with green hydrogen (i.e., hydrogen produced by electrolysis using renewable electricity sources), more fuels can be created with zero emissions. Therefore, synthetic fuels produced with excess electricity from renewable sources represent an attractive solution for the decarbonization of mobility and those transport applications that are not suitable for electrification.

In [11], the authors presented the results of the analysis of all stages of the energy conversion from the source of electricity, i.e., wind, solar, or hydro, to the final application, i.e., a vehicle traveling a certain number of miles. The fuels studied are hydrogen, methane, methanol, dimethyl ether, and diesel. While their production process is analyzed based on the literature, the usage of these fuels was analyzed based on the dynamometer measurement data of various EURO-6b passenger vehicles. This analysis is essential, as the electrification of passenger vehicles may be unsuitable for some applications due to one or more different effects [12]:

- The overall weight may be excessive if the vehicle is to be very light;
- The achievement of a high degree of autonomy;
- The need for rapid replenishment time.

The authors in [11] presented a Well-to-Mileage (WtM) comparison based on the fuel type. Finally they derived the energy consumption of a vehicle driving a pre-defined speed profile. The authors derived the energy consumption from a simple vehicle model and used the results as part of the WtM analysis. For each fuel, the following were considered: (i) production/synthesis process; (ii) compression (if necessary, as for hydrogen); (iii) transportation; (iv) refueling process.

References

1. Climate Watch: World Resources Institute. Available online: https://www.wri.org/initiatives/climate-watch (accessed on 14 September 2022).
2. Ritchie, H.; Roser, M.; Rosado, P. Energy Mix. 2022. Available online: https://ourworldindata.org/energy (accessed on 14 September 2022).
3. Moro, A.; Lonza, L. Electricity carbon intensity in the European Member States: Impacts on GHG emissions of electric vehicles. Transp. Res. Part D 2018, 64, 5–14.
4. Del Pero, F.; Delogu, M.; Pierini, M. Life Cycle Assessment in the automotive sector: A comparative case study of Internal Combustion Engine (ICE) and electric car. Procedia Struct. Integr. 2018, 12, 521–537.
5. Climate Transparency Report. 2020. Available online: https://www.climate-transparency.org/g20-climate-performance/the-climate-transparency-report-2020 (accessed on 16 September 2022).
6. Eichberger, C.; Jungmeier, G. Environmental Life Cycle Impacts of Automotive Batteries Based on a Literature Review. Energies 2020, 13, 6345.

7. Gallagher, K.G.; Trask, S.E.; Bauer, C.; Woehrle, T.; Lux, S.F.; Tschech, M.; Lamp, P.; Polzin, B.J.; Ha, S.; Long, B.; et al. Optimizing Areal Capacities through Understanding the Limitations of Lithium-Ion Electrodes. J. Electrochem. Soc. 2016, 163, A138.
8. Rievaj, V.; Gaňa, J.; Synák, F. Is hydrogen the fuel of the future? Transp. Res. Procedia 2019, 40, 469–474.
9. European Commission. Energy—Biofuels. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/default_values_biofuels_main_reportl_online.pdf (accessed on 20 October 2022).
10. Rothbart, M. e-Fuel Production via Renewables and the Impact on the In-Use CO2 Performance; SAE Technical Paper 2020-01-2139; SAE International: Warrendale, PA, USA, 2020.
11. Hänggi, S.; Elbert, P.; Bütler, T.; Cabalzar, U.; Teske, S.; Bach, C.; Onder, C. A review of synthetic fuels for passenger vehicles. Energy Rep. 2019, 5, 555–569.
12. Jadhav, S.G.; Vaidya, P.D.; Bhanage, B.M.; Joshi, J.B. Catalytic carbon dioxide hydrogenation to methanol: A review of recent studies. Chem. Eng. Res. Des. 2014, 92, 2557–2567.