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Assessment of Passenger Car Electrification by Yearly Total CO_2 Emission

István LERCHNER[1], Máté ZÖLDY[2]

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[1] istvan.lerchner@zalazone.hu, Automotive Proving Ground Zala Ltd., Zalaegerszeg, Hungary
[2] zoldy.mate@gtk.bme.hu, Department of Environmental Economics and Sustainability, Budapest University of Technology and Economics, Budapest, Hungary

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ABSTRACT

Global warming demands urgent action to reduce greenhouse gas emissions, with road transport being a major contributor. Electrification of passenger cars is widely promoted as a key mitigation strategy; however, its real-world impact remains debated. This study develops a calculation framework to estimate annual fleet-level greenhouse gas emissions based on actual consumption data, vehicle type distribution, age and mileage. Using this method, short- and mid-term drawbacks of electrification are quantified alongside long-term benefits through scenario analysis aligned with the European Union 2035 target. Results indicate that electrification begins to deliver net emission reductions after 2032, achieving a 5.3% decrease by 2035 compared to an internal combustion engine fleet. These findings highlight the temporal dynamics of electrification and provide evidence-based insights for policymakers and industry stakeholders.

KEYWORDS

CO_2; greenhouse gas emission; electrification; battery; real-world consumption; life cycle assessment.

1. INTRODUCTION

According to the IPCC (Intergovernmental Panel on Climate Change) report [1], the global surface temperature in 2011–2020 is 1.1°C above the 1850–1900 level. Overstepping a specific temperature, e.g. 1.5°C, results in irreversible changes; therefore, immediate actions are required. As road transport in the EU contributes 24% of the total anthropogenic greenhouse gas (GHG) emissions [2], it is obvious that measures must be taken to reduce emissions in this field too. Beyond vehicle emissions, the automotive industry sector contributes directly, e.g. through manufacturing, and indirectly, e.g. through fuel supply, to GHG emissions. Hence, the effectiveness of a measure or a new technology needs to be evaluated in a broader aspect, considering the whole lifecycle beyond the technology or product GHG emissions itself, taking into account the connecting infrastructure or required services.

In the automotive sector, electrification, and within that, the battery electric vehicle (BEV), is actually one of the key measures towards GHG emission reduction [3]. Even if in several segments, like heavy-duty vehicles, the technology is still not competitive today, in the passenger car segment, it continuously gains greater market share. The spread is not homogeneous in the big markets and regions, nor in different countries, depending on several influencing factors like economic and political situations, customer preferences, subsidies, etc., even though the growing number of BEVs is obvious.

The global warming impact of BEVs was initially evaluated by comparing them to internal combustion engine vehicles (ICEVs) based only on local emissions, which are obviously zero for BEVs. It was realised very soon that a realistic comparison needs to be done based on life cycle assessment (LCA) [4]. The LCA methodology considers the whole "life" of the vehicle for GHG emission evaluation, meaning production (including raw material extraction and manufacturing), distribution, fuel or electricity supply (WTT: well-to-tank), vehicle local emissions (TTW: tank-to-wheel), maintenance and recycling.

Numerous studies have investigated the impact of BEVs on global warming compared to ICEVs using the LCA methodology, often based on reference vehicles. These studies show a wide range of results depending on highly influential factors such as production location, energy mix, battery lifetime, total considered mileage of the vehicle and vehicle fuel and energy consumption [5]. Typically, BEVs have higher production GHG emissions than ICEVs but lower emissions in operation, which means there could be a break-even point. If and at what mileage this break-even point is reached depends on the previously mentioned factors. Although these vehicle-to-vehicle comparisons with reference vehicles are scientifically correct in a laboratory environment, they do not take into account several additional boundaries that influence the real GHG emission impact for a region, city or country. As a further step, several studies have investigated the BEV's effect in a broader aspect. Yan et al. [6] estimated passenger car GHG emission for the metropolis Singapore based on 30,000 registered vehicles by LCA with a lifespan mileage of 160,000 km, and compared the break-even mileage between each powertrain type. It presented a break-even point for BEV compared to ICEV of 34,169 to 43,495 km. Further on, compared scenarios by GHG emission in 2040 and showed a benefit of 16% to 58% by electrification with low-carbon electricity generation. Maglic et al. [7] set up models for emission calculation of Rijeka city roads in the peak hours and predicted the emission for 2030 in kg/km unit for various road segments. The study evaluated the impact of prohibiting measures of certain vehicle categories, e.g. those that do not conform to the latest standards of emission. Model results showed an average CO_2 emission reduction of 20% in 2030 compared to the reference year 2017. Mintzia et al. [8] compared roadway and railway for passenger and freight transport between Athens and Thessaloniki by CO_2 emissions of construction and operation. Whereas the operational emission by railway resulted in hardly 17% less emission in passenger transport, at freight transport, the operational emission was already 10-14 times lower by railway. Burchart-Korol et al. [9] carried out a comparative LCA analysis of BEVs and ICEVs for Poland and the Czech Republic by applying various renewable electric energy generation scenarios for vehicle charging with predictions until 2050. The results showed that BEVs have lower GHG emissions; nevertheless, renewable energy plays a major role. Furthermore, vehicle and battery production are high-impact factors as well. Rinawati et al. [10] analysed potential CO_2 reduction by passenger car electrification for Japan towards carbon neutrality in 2030, taking into account the specific characteristics of the Japanese market with a high share of hybrid vehicles. The study presented for both government-targeted roadmap and aggressive electrification scenarios higher cradle-to-grave emissions in 2030 than the business-as-usual scenario, with lower electrified powertrain vehicle share as a consequence of high battery production emissions. Faria et al. [11] investigated the impact of electricity mix and use profile in LCA with four ICEVs, one PHEV and three BEVs as reference vehicles. In their conclusions, electric vehicles can be more environmentally friendly than ICEVs; however, the eco-driving attitude has a high impact by affecting up to a 47% difference in electric consumption.

Some simplifications of previous studies:

- Fuel and energy consumption are estimated based on WLTP (Worldwide Harmonised Light Vehicle Test Procedure [12]), which, due to the standardised procedure and cycle, enables a fair comparison. Nevertheless, the real-world consumption differs from the WLTP value, and accordingly, the absolute GHG emission is underestimated.
- One or some reference vehicles are chosen for the fleet of vehicles estimation, and it is not clear how and if these specific vehicles represent the whole vehicle fleet.
- The LCA-based calculation of total lifetime GHG emissions includes all emission sources, such as those from vehicle production and operation. Dividing this total emission by the expected vehicle lifetime mileage (in kilometres) yields a value expressed in g/km. However, this approach implies that emissions are evenly distributed across all driven kilometres, which is not the case. For instance, the operational emissions of BEVs are typically lower than those of ICEVs. Therefore, such a comparison between different powertrain technologies can be misleading.
- The break-even point between BEV and ICEV is defined in terms of mileage, but it is highly relevant when the emission is generated. A BEV with low customer yearly mileage could reach the break-even point only after many years, although a BEV first after the break-even point could be considered as a GHG emission reduction measure.

This study applies a holistic approach [13] in researching the BEV GHG emission effect compared to ICEV, not by the classical LCA methodology, but using parts of it. Instead of focusing on the vehicle's total lifecycle GHG emissions, it researches the GHG emissions based on the time when these are generated. It considers the

GHG emission categories as in LCA (production, WTT, TTW, recycling), but cumulates them for the year when these are generated. The BEVs' GHG emission impact is investigated in this study for the Hungarian market based on real data of the whole passenger car fleet, market-specific fuel, energy consumption and energy mix, average yearly mileage, vehicle categories, market share and fleet composition. Hungary was chosen as a pilot to present the research results, as it represents the central European area with high data availability.

2. METHOD

A model was set up that can be easily adapted to other markets with market-specific input parameters. The model calculates the GHG emissions by Hungarian passenger cars for each year until 2035. For 2023 and previous years, the calculation is based on statistical data without assumptions. From the year 2024 onwards, the calculation is built on different passenger car fleet development models. The study also considers production emissions, although in most cases, these do not contribute to Hungarian state GHG emissions as many production locations are outside of Hungary. Therefore, the results are not comparable to the Hungarian state commitments. The study accepts this as GHG emission reduction is a global challenge, and the evaluation of the spread of BEVs can be fairly evaluated in this broader aspect.

2.1 Fleet and prognosis

There has been continuous growth in the number of passenger cars in Hungary since 2012, as well as in the number of new registered vehicles until 2019, when it reached the highest value of 162,944 [14]. Even though market growth continued after the COVID crisis, the number of new registered vehicles decreased year by year, and only in 2024, with 121,607 registrations, did it achieve a higher value compared to the previous year. As the Hungarian motorisation value per inhabitant is still one of the lowest in the European Union, a moderate growth in new vehicle registrations and passenger car fleet size is expected. The model uses a conservative estimation until the year 2035, according to *Figure 1*, which results in a total fleet of 5,161,779 passenger cars in 2035. Yearly fleet growth differs from the number of new registered vehicles, as there are additional registrations of imported second-hand vehicles, and there are also vehicles withdrawn from the market.

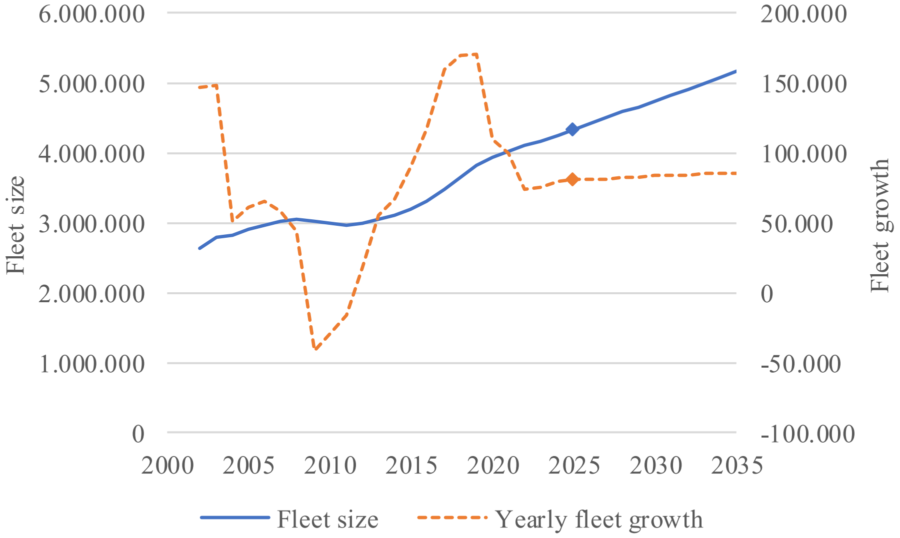

Figure 1 – Yearly passenger car fleet size and growth in Hungary (2002–2024 statistical data [14], 2025–2035 prognosis)

The Hungarian fleet distribution according to fuel type in 2023 is shown in *Figure 2*, which serves as the base year for estimation. To simplify the model, the estimation will be separated into two vehicle powertrain categories: the first one is BEV, and the other is ICE-based vehicles, including gasoline, diesel, LPG (liquefied petroleum gas), HEV (hybrid electric vehicle) and PHEV (plug-in hybrid electric vehicle). Other powertrain types like CNG (compressed natural gas) or FCEV (fuel cell electric vehicle) have an insignificant market share in Hungary, and no change is expected from today's perspective, so these are not considered. All vehicles withdrawn from the market are taken as ICEVs.

Based on the two vehicle powertrain categories, three scenarios are calculated:

1) Full ICE-based scenario (FI): Considers no further BEV market share until 2035, i.e. no new BEV registrations from 2025.
2) Full BEV scenario (FB): Considers that every year, all new registered vehicles are BEVs until 2035.
3) EU 2035 scenario (EU2035): Considers the ban of new ICE-based vehicles from 2035 with a linear phase-out of ICE-based vehicles and a linear ramp-up of BEVs (*Figure 3*).

Note that in 2035, by the full ICE-based scenario, the BEV share will reduce to 0.8%, by the full BEV scenario will rise to 45.1% and by the EU2035 scenario to 20.8%.

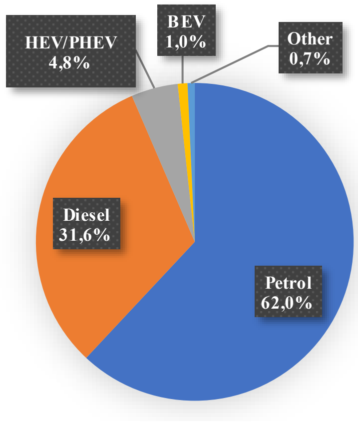

Figure 2 – Passenger car fleet by fuel type in Hungary in 2023

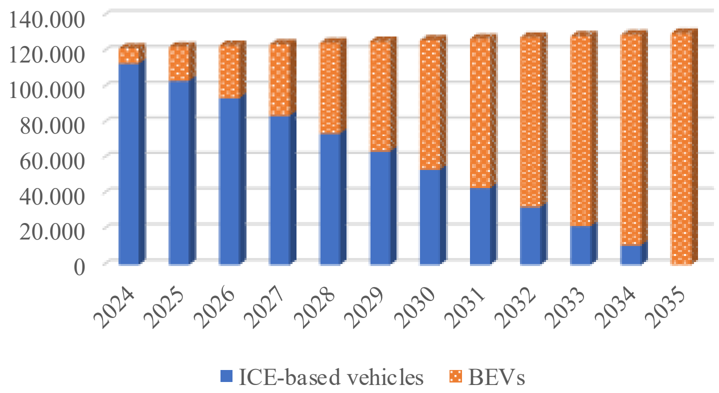

Figure 3 – Yearly new passenger car registration by the EU2035 scenario

2.2 GHG emission in operation

Operational GHG emissions are considered to be TTW, WTT and maintenance. The expected battery lifetime is a crucial parameter for considering the emissions from maintenance. If the battery lifetime is shorter than the vehicle lifetime, then a battery change or refurbishment is required, which significantly increases the maintenance impact at BEVs. On one side, battery technology is developing means longer lifetime; on the other side, more frequent fast and ultrafast charging, which is becoming more available following the Alternative Fuels Infrastructure Regulation of the EU [15], increases battery degradation. [16] Furthermore, vehicle user market experiences are still limited due to the relatively low age and number of BEVs on the market. These contradictory effects challenge the estimation of GHG emissions by maintenance. As a simplification of this study, the maintenance GHG emissions, including battery change and refurbishment, are not considered. Due to the period under examination until 2035, this does not worsen the result, when it is expected that the average battery lifetime is over 12 years. Furthermore, the maintenance GHG emissions coming from parts and fluid replacement (except the battery) or regular inspection are much lower than the other operational GHG emissions: TTW and WTT [17].

Tank-to-wheel CO_2 emission

The GHG emissions during operation depend primarily on the real-world fuel consumption of ICE-based vehicles. This study aims to calculate the GHG emissions of the passenger car fleet of Hungary, unlike several previous studies that compare reference vehicles based on standardised fuel consumption values. The yearly recorded new registered vehicle database [18] comprises data for each new registered vehicle. By processing these data for several years back, the following figures are presented: WLTP CO_2 emissions in *Figure 4* and the average mass of new registered vehicles in *Figure 5*. When the yearly total number of newly registered vehicles is not high enough for a specific powertrain, i.e. below 100, the corresponding data are not presented. CO_2 emission data according to WLTP are available from 2018 to some extent and for all vehicles from 2020. For vehicles with only NEDC (New European Driving Cycle) fuel consumption data, a WLTP/NEDC correction factor of 1.21 was applied [19]. The average vehicle mass of all powertrain categories is rising, particularly for BEVs in recent years, aligned with the growing battery capacity (*Table 1*). The average fuel consumption for diesel ICEVs is higher than for gasoline ICEVs due to the higher vehicle mass. These observations clearly point out that comparing different powertrain technology vehicles with similar vehicle mass, size and performance results in sufficient technology comparison on a vehicle level, but does not provide a representative conclusion for a specific researched market or fleet.

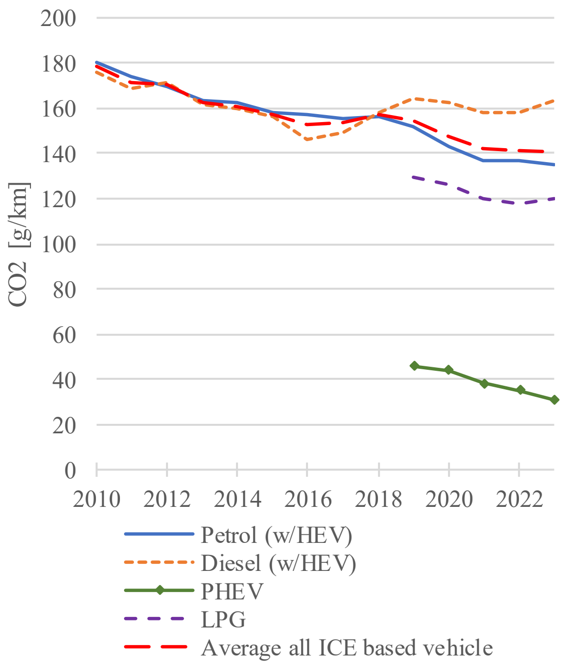

Figure 4 – WLTP CO₂ emission of new registered vehicles by fuel type (g/km)

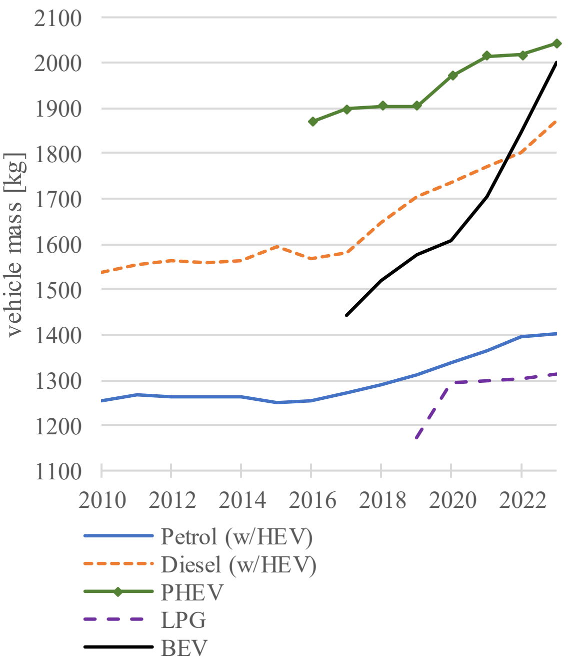

Figure 5 – Average vehicle mass in-running-order of new registered vehicles by fuel type (kg)

Table 1 – Average vehicle mass in-running and average battery nominal capacity of BEVs for the Hungarian passenger car market

Years	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Battery average nominal capacity [kWh]	32.8	37.6	42.8	45.3	54.5	63.7	74.0
Average BEV vehicle mass in-running-order [kg]	1442	1517	1575	1607	1705	1847	2000

Calculation of real-world TTW GHG emissions for ICE-based vehicles from WLTP CO_2 emissions requires additional steps. The real-world fuel consumption needs to be estimated as it differs from WLTP fuel consumption. Since 2021, the OBFCM (on-board fuel consumption monitoring [26]) has been mandatory for all new vehicles in the European Union. This provides statistical data about fuel consumption in customer use. The JRC report analyses these data and defines the factor between WLTP and real-world fuel consumption for different powertrain types [20]. Generally, fuel consumption in real customer use was higher than WLTP consumption, on average 20.1% for petrol, 17.9% for diesel, 19% for LPG, and an extreme 264.4% higher for PHEVs. The huge difference for PHEVs resulted from the general customer use of rarely charging PHEVs.

Setting 2023 as the base year, these factors are applied to the WLTP data of newly registered vehicles. For estimating the emissions of the entire Hungarian fleet, not just the newly registered vehicles of 2023, a vehicle age-based factor needs to be considered, which is representative of the investigated market with all vehicles, both new and older ones, together. Based on the average WLTP CO_2 emissions of all ICE-based newly registered vehicles (see *Figure 4*), the CO_2 emissions decreased by 27% between 2010 and 2023, i.e. over 13 years. Applying linear extrapolation, the projected reduction over 16 years is 29%. Given that the average vehicle age in Hungary is 15.8 years [14], a value of 29% was applied as an added factor to the new vehicle's CO_2 emissions to estimate the whole fleet emissions for both new and older cars together.

Considering the real customer fuel consumption factors and the vehicle fleet age factor based on the Hungarian passenger car fleet distribution in 2023 (*Table 2*), the fleet average TTW CO_2 emission for ICE-based vehicles is 218.8 g/km in 2023. The average CO_2 emission of the newly registered vehicles is 165.1 g/km in real-world use and 134.6 g/km according to WLTP. The significant gaps between these values show how misleading a purely WLTP-based CO_2 emission estimation can be for a specific market, country, region or city. To avoid confusion, note that the WLTP-based average CO_2 emission of 127.4 g/km for newly registered vehicles in Hungary in 2023, as presented by the EEA (European Environmental Agency) [18], differs from this study's calculated value of 134.6 g/km because no BEVs were considered in the study calculation. This allows ICE-based vehicles and BEVs to be treated separately in the model estimation for 2024-2035. Another potential source of confusion is the WLTP-based EU CO_2 fleet target of 93.6 g/km from 2025, which refers to the reference vehicle mass of 1,609.6 kg with additional super-credits and ZLEV (zero and low emission vehicle) factors included [21].

Table 2 – Passenger car fleet size and distribution in Hungary [14]

Fuel type	2022	2023
Petrol	2,583,328	2,583,465
Diesel	1,294,087	1,315,322
HEV/PHEV	156,472	198,235
Other	30,406	30,417
BEV	29,836	41,212
Total	4,094,129	4,168,651

Calculation of the TTW CO_2 emission of ICE-based vehicles for the fleet and for the new registered vehicles for the years between 2025-2035, as in (1) applied to previously defined scenarios individually (FI, FB, EU2035).

$$co_{2(/km)fleet(n+1)} = co_{2(/km)fleet(n)} + \frac{Q_{new(n+1)}}{Q_{fleet\,(n+1)}} \cdot \left(co_{2(/km)\,new(n+1)} - co_{2(/km)\,fleet(n)}\right) \tag{1}$$

where:

$co_{2(/km)fleet(n)}$ – average CO_2 emission for the fleet in year n (g/km)
$co_{2(/km)\,new(n)}$ – average CO_2 emission for the new registered vehicles in year n (g/km)
$Q_{new(n)}$ – number of new registered vehicles in year n
$Q_{fleet\,(n)}$ – number of vehicles in the fleet in year n

The CO_2 emission reduction of newly registered ICE-based vehicles is expected to continue, although the pace is questionable. The yearly reduction between 2020-2023 was 2.6% on average in Hungary. Nevertheless, due to the diminishing market share and the expected ban of ICEVs in 2035 in the EU, this study predicts a linear decline to a yearly reduction of only 0.1% by 2035.

The yearly average mileage needs to be estimated to calculate the total TTW CO_2 emissions for the fleet of ICE-based vehicles. Several data sources are available for the market-specific yearly average mileage based on questionnaires or statistical data, but these are different from the mathematical average, which is required for this study. The study uses a new method for yearly mileage estimation based on the yearly fuel sales of fuel stations. This is a mandatory reporting by all fuel stations, separated by fuel types and vehicle types, and the dataset is compiled by the Hungarian Energy and Public Utility Regulatory Authority [22]. In the last reported year, 2022, passenger cars used 1,369,178 tonnes of petrol, 1,108,106 tonnes of diesel, and 13,000 tonnes of LPG. This is equivalent to 1,837,822,819 litres of petrol, 1,331,858,173 litres of diesel, and 23,400,000 litres of LPG, which further equates to 4,263 kt CO_2 emissions from petrol, 3,529 kt CO_2 emissions from diesel, and 35 kt CO_2 emissions from LPG, in total 7,828 kt CO_2 emissions. This results in a yearly average mileage of 8,923 km using the average fleet TTW CO_2 emissions in g/km calculated for the year 2022 (using the same calculation method as for the year 2023). The calculated mileage is used for the yearly TTW CO_2 emission estimation for ICE-based vehicles. The EEA reported 8,305 kt CO_2 emissions by cars for Hungary in 2022 [2], which means a deviation of 6% from the previously calculated data. The total fleet TTW CO_2 emission for the year n is calculated as in (2) for ICE-based vehicles. As the tailpipe CO_2 emission of ICEVs is 99% of the total GHG tailpipe emission, it is assumed that $CO_{2\_eq(TTW\,ICEV)} = CO_{2\_(TTW\,ICEV)}$.

$$CO_{2(TTW\,ICEV)fleet(n)} = Q_{ICEV\,(n)} \cdot co_{2(/km)\,fleet(n)} \cdot s_{yr} \tag{2}$$

where:

$Q_{ICEV\,(n)}$ – number of ICE-based vehicles in the fleet in year n
$co_{2(/km)\,fleet(n)}$ – average CO_2 emission for the fleet in year n (g/km)
s_{yr} – average yearly mileage (km), 8923 km for Hungary as previously calculated

At fuel stations, all available fuels have mandatory bio components: ethanol in E10 for petrol ICEVs and biodiesel/FAME in B7 for diesel ICEVs. However, premium fuels with low or without direct biocomponent blending are still available. The biocomponent of fuel is considered CO_2 neutral, meaning this part has to be subtracted from the calculated CO_2 emissions. Considering the Hungarian ICEV composition (the proportion of diesel and petrol ICEVs) and the minor premium fuel sales [23], an average weighted factor of 9% was applied. The final TTW CO_2_eq emission calculation includes a reduction according to the biocomponents of the fuel.

Well-to-tank CO_2 emission

ICE-based vehicles WTT CO_2_eq emission calculated as in (3) for the year n.

$$CO_{2\_eq(WTT\,ICEV)fleet(n)} = CO_{2\,(TTW\,ICEV)fleet(n)} \cdot \frac{1}{fac_{\frac{CO2}{fuel}}} \cdot co_{2\_eq(WTT\,fuel)} \qquad (3)$$

where:
$CO_{2(TTW)fleet(n)}$ – total fleet TTW CO_2 emission for the year *n (g)*
$fac_{\frac{CO2}{fuel}}$ – tailpipe CO_2 emission of 1 L fuel combustion (g/L), calculated value of 2397 g/L for Hungarian fleet distribution based on petrol and diesel factors [24]
$co_{2\_eq(WTT\,fuel)}$ – CO_2_eq emission of 1 L fuel by fuel production and transport to the fuel station (g/L). This is 590 g CO_2_eq/L for the Hungarian fleet by calculation based on the values of 5.5 CO_2_eq g/MJ for petrol and 7.2 CO_2_eq g/MJ for diesel [25]

BEV WTT emissions depend on the electric consumption of the vehicle, the charging losses and CO_2_eq emissions from electricity generation. The end-customer representative electric consumption of a BEV in real use is similarly complicated as fuel consumption for ICE vehicles. WLTP-based rated electric consumption of newly registered vehicles is available [18]. Rated electric consumption means that the charging losses are included. *Figure 6* presents the average WLTP rated electric consumption of all newly registered BEVs in Hungary. Just like for ICEVs, BEVs' real-world consumption is also higher than the WLTP value, on average by 25% [26], so the average real-world electric consumption of newly registered BEVs in Hungary in 2023 is 217.2 Wh/km. As the WLTP electric consumption has not changed in recent years, and knowing that BEVs are relatively new vehicles, the 2023 consumption value is taken as the fleet electric consumption. Despite increasing vehicle mass, the electricity consumption has been relatively stable in recent years. Expecting no further significant battery capacity increase and corresponding vehicle mass increase, a slight efficiency improvement is considered for 2024–2035: 8% for 2024, 2% for 2035 and linear in between. Although PHEVs' charging contributes to WTT emissions, this was not considered due to the previously mentioned rare customer charging behaviour.

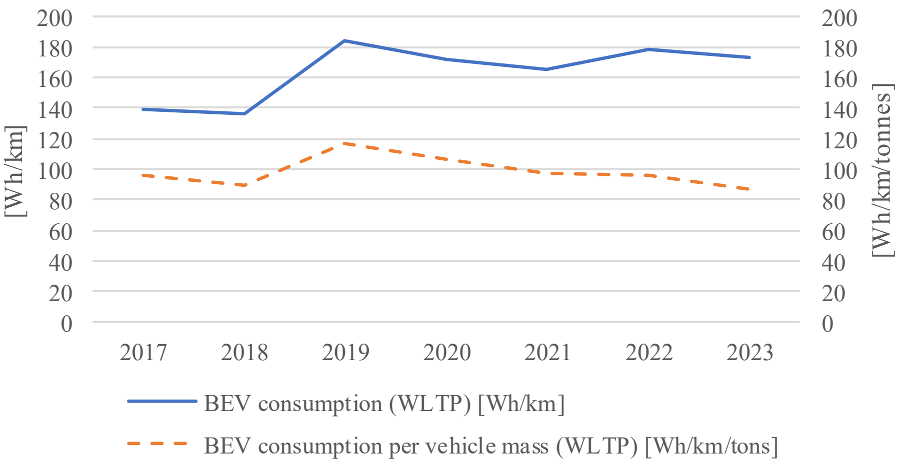

Figure 6 – New registered BEVs average WLTP-rated electric consumption

Total WTT CO_2_eq emission calculated as in (4) for the whole fleet of BEVs for the year n.

$$CO_{2\_eq(WTT\,BEV)fleet(n)} = c_{BEV\,fleet(n)} \cdot co_{2_{eq}(TTW\,el)(n)} \cdot Q_{BEV(n)} \cdot s_{yr} \tag{4}$$

where:

$c_{BEV\,fleet(n)}$ – BEV fleet average real-world electric consumption in year n (Wh/km)
$co_{2\_eq(TTW\,el)\,(n)}$ – CO_2_eq emission of 1 kWh electric energy generation in year n (g/kWh)
$Q_{BEV(n)}$ – number of BEVs in the fleet in year n
s_{yr} – yearly mileage (km), 8923 km for Hungary, as previously calculated in the study

$co_{2\_eq(TTW\,el)\,(n)}$ applied values in the study for 2023–2035 are given in *Table 3*. The dataset for 2023 is from the EEA report [27], while the forecast for 2024–2035 is based on the National Energy and Climate Plan of Hungary [28]. It considers the operational GHG emissions of electricity generation, meaning renewable and nuclear sources are assigned a zero factor. Lifecycle greenhouse gas emissions also include the GHG emissions from power plant establishment, which this study does not take into account, as these emissions were not generated in the specific researched year for an existing plant. Research on power plant establishment in the case of expected higher electric energy needs due to a higher BEV market share is outside the scope of this study.

Table 3 – CO_2_eq emission intensity of electricity generation in Hungary in g/kWh; 2024-2035 forecast

Years	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
CO_2_eq [g/kWh]	*154.0*	*150.7*	*147.4*	*144.1*	*140.8*	*137.5*	*134.3*	*131.0*	*127.7*	*124.4*	*121.1*	*117.8*	*114.5*

2.3 GHG emission by production and recycling

Numerous studies have analysed the GHG emissions of the production of different powertrain technology vehicles; many focus on comparing BEVs against ICEVs on a reference vehicle basis using LCA methodology, while some focus on influencing factors like battery capacity, production location and energy mix. These studies present a wide range of values of 39–272 kg CO_2_eq/kWh for the battery production emission [29][30][31]. Recycling is considered a GHG emission gain by obtaining materials with lower emissions through recycling than through raw material extraction. This study aims to define the Hungarian market-specific average GHG emissions from vehicle production. The average nominal battery capacity of newly registered BEVs in Hungary in 2023 was 74 kWh [18] [32]. As the battery location (EU, USA, China) and technology data (NMC, LFP) are regularly not publicly available for the vehicles, an average value of 71 kg CO_2_eq/kWh was taken for battery production and -15 kg CO_2_eq/kWh for recycling [33]. For vehicle body production GHG emissions, a specific value of 4.56 kg CO_2_eq/kg_vehicle_mass and -2.93 kg CO_2_eq/kg_vehicle_mass for recycling were applied [34]. The average mass in-running-order of newly registered BEVs in Hungary in 2023 was 2000 kg. Subtracting the driver's mass of 75 kg, the vehicle production mass is 1925 kg. Further subtracting the battery mass of 370 kg for a 74 kWh battery, the body mass is 1555 kg. The newly registered ICE-based vehicles in 2023 have an average weight of 1526 kg mass in-running-order, meaning a vehicle production mass of 1451 kg. Based on these data, the average GHG emissions of a newly registered BEV in Hungary in 2023 are 12.3 tonnes CO_2_eq from production and -5.7 tonnes CO_2_eq from recycling. For ICE-based vehicles, the values are 6.6 tonnes CO_2_eq from production and -4.3 tonnes CO_2_eq from recycling. These values were taken as constant for the yearly GHG estimation for 2024–2035. The recycling effect was applied in the production year of the new vehicles.

The GHG emission by production subtracted with recycling for each year is calculated as in (5) for the total fleet, where (5) is calculated separately for BEVs and ICEVs in the model.

$$CO_{2_{eq(prod-re)(n)}} = \left(CO_{2\_eq(prod)} + CO_{2\_eq(re)}\right) \cdot Q_{new(n)} \tag{5}$$

where:

$CO_{2\_eq(prod)}$ – GHG emission by production of one vehicle (tonnes)
$CO_{2\_eq(re)}$ – GHG emission gain by recycling of one vehicle as a negative value (tonnes)
$Q_{new\,(n)}$ – number of new registered vehicles in the year n

3. RESULTS

The total GHG emission in each year is calculated as in (6) for the total fleet based on the previous calculations.

$$CO_{2_{eq(total)fleet(n)}} = CO_{2_{eq(prod-re)(ICEV)(n)}} + CO_{2_{eq(prod-re)(BEV)(n)}} + CO_{2_{eq(WTT\,ICEV)fleet(n)}} + \\ + CO_{2_{eq(WTT\,BEV)fleet(n)}} + CO_{2_{eq(TTW\,ICEV)fleet(n)}} \tag{6}$$

The yearly GHG emissions are presented for the previously chosen scenarios in *Figure 7*, where operational emissions are the sum of WTT and TTW. The full ICEV scenario shows a continuous increase in the yearly total GHG emissions of the fleet due to the growing fleet with only ICE-based vehicles, resulting in 10.5% more yearly GHG emissions in 2035 compared to 2023. Both the full BEV and EU2035 scenarios initially show an increase in yearly emissions compared to the 2023 base year, but later this changes to a decrease. While the full BEV scenario results in a 3.8% reduction in yearly emissions by 2035 compared to 2023, the EU2035 scenario still results in 6.8% higher yearly emissions by 2035 compared to 2023. Nonetheless, both scenarios show a benefit in 2035 compared to the full ICEV scenario: the full BEV scenario shows a reduction of 14.8%, while the EU2035 scenario shows a reduction of 5.3%.

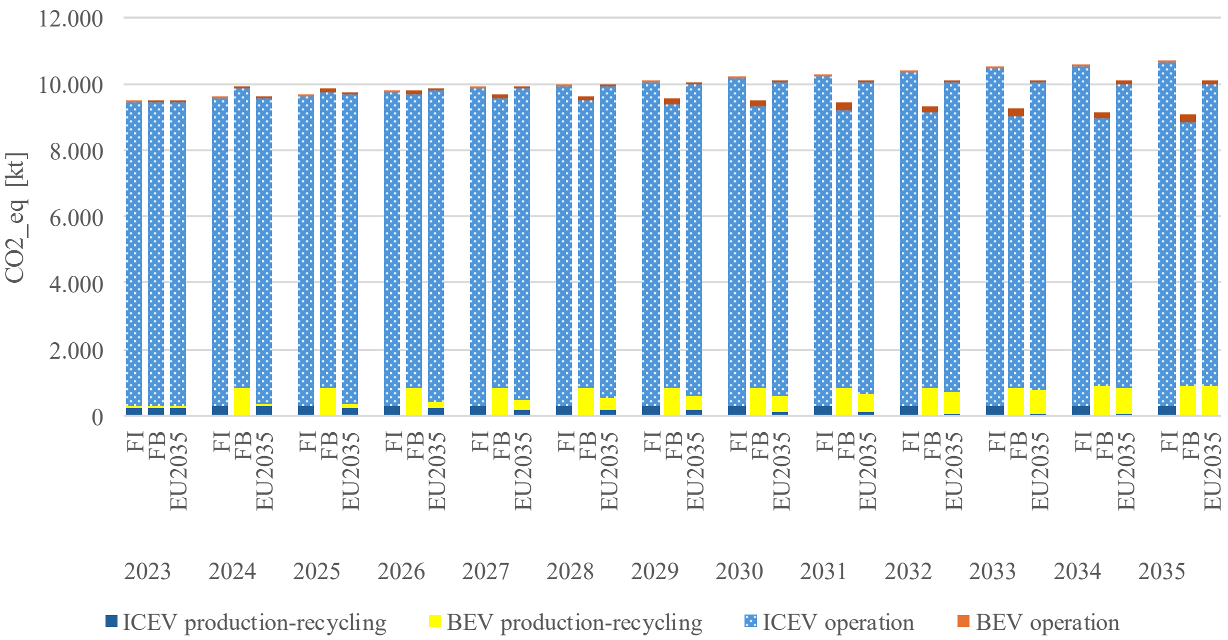

Figure 7 – Yearly total GHG emission by Hungarian passenger car fleet for full ICEV (FI), full BEV (FB) and EU2035 scenarios

For a better comparison, *Figure 8* presents the yearly and cumulative differences between the FB and FI scenarios, and *Figure 9* presents the differences for the EU2035 and FI scenarios. Neither the full ICEV scenario nor the full BEV scenario will happen; nevertheless, they present strict boundaries. The comparison base is always the full ICEV scenario, as the aim is to evaluate the BEV GHG emission impact. Noticeably, after higher yearly emissions in the earlier years, both BEV scenarios reach the break-even point: the full BEV scenario after 3.2 years in 2027, and the EU2035 scenario after 5.2 years in 2030, resulting in lower yearly emissions. Nonetheless, the cumulative emissions reach the break-even point later: the full BEV scenario after 5.2 years in 2029, and the EU2035 scenario after 7.1 years in 2032. Only after the cumulative break-even point does a BEV scenario have an advantage regarding GHG emissions compared to the full ICEV scenario. The extent of overshooting until the yearly break-even is also relevant due to mid-term climate warming targets in view of irreversibility. By the full BEV scenario, 610 kt CO_2_eq more are produced until the yearly break-even, which corresponds to 6.2% of the yearly total of 2023, while for the EU2035 scenario, 169 kt CO_2_eq more are produced, corresponding to 1.7%.

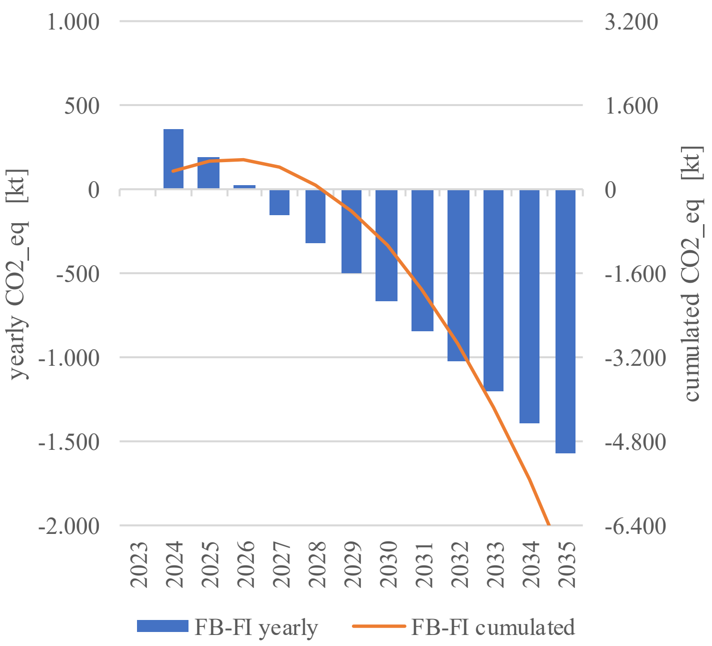

Figure 8 – Difference full BEV (FB) – full ICEV (FI) scenario yearly and cumulative

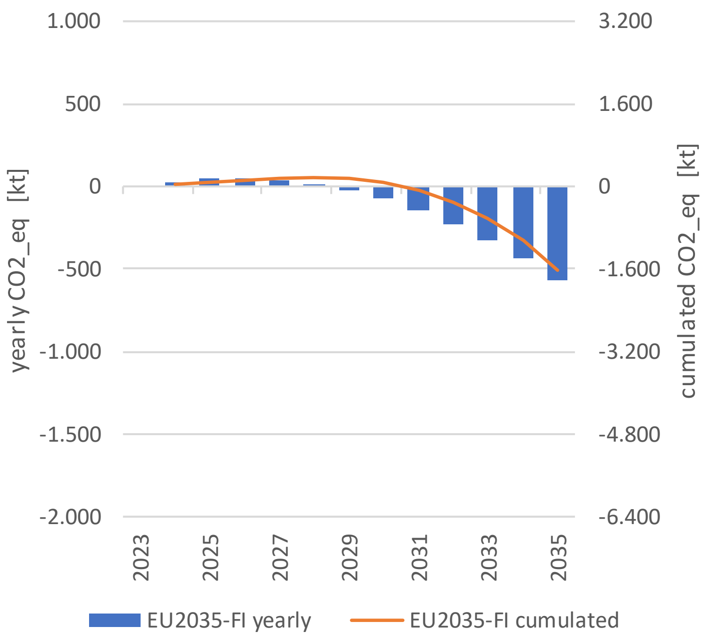

Figure 9 – Difference EU2035 – full ICE (FI) scenario yearly and cumulative

4. SENSITIVITY ANALYSIS

The model robustness was analysed based on yearly total GHG emission calculated for 2035 for all three scenarios, with the variation of 8 parameters separately with -10% and +10%. BEV electricity consumption is excluded from the variation parameters, as this has the same effect as the CO_2_eq intensity of electricity generation. *Figure 10, Figure 11 and Figure 12* summarise the results for the three scenarios. Noticeably, the ICEV fuel consumption and average yearly mileage have in all three scenarios the strongest influence on yearly total emission, which is understandable as in 2035 the ICEV share is still the highest in all scenarios. Emissions by production have less influence, as the operational emissions have a much higher portion in total yearly emissions.

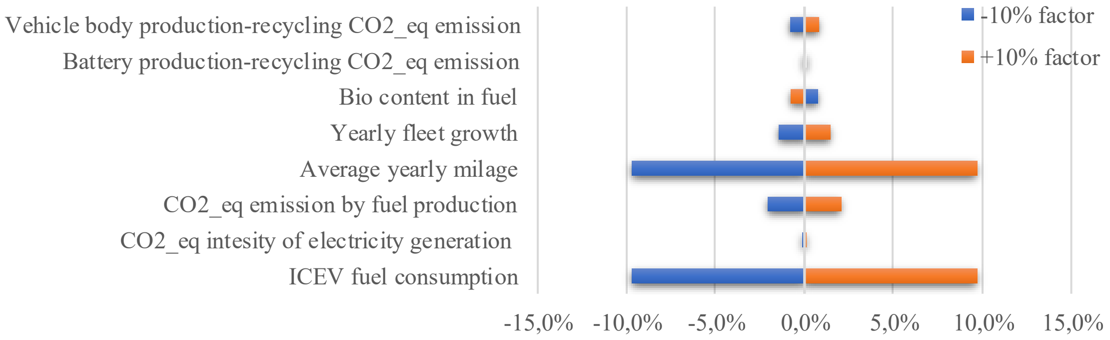

Figure 10 – Variation of yearly total GHG emission in 2035 by the full ICEV (FI) scenario

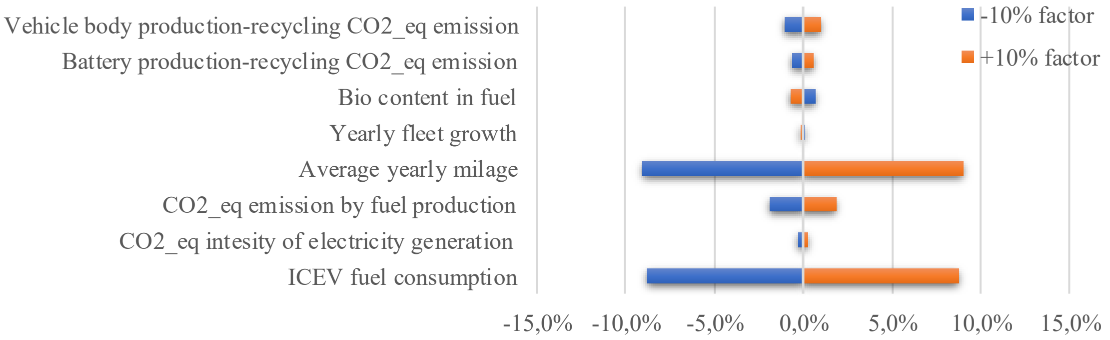

Figure 11 – Variation of yearly total GHG emission in 2035 by the full BEV (FB) scenario

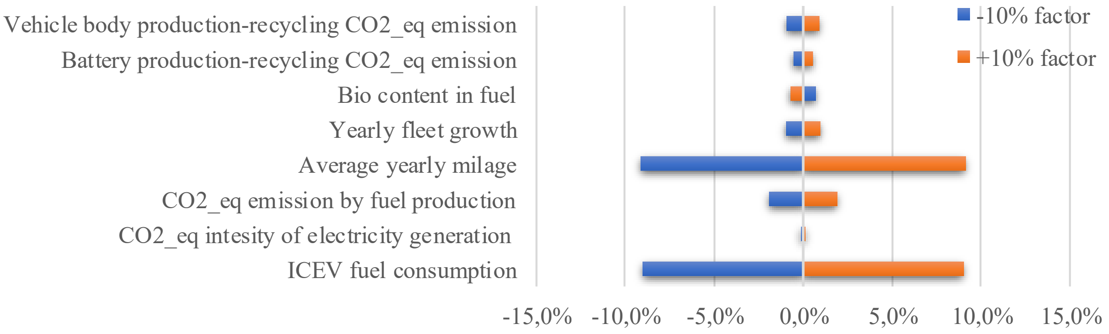

Figure 12 – Variation of yearly total GHG emission in 2035 by the EU2035 scenario

The variation of the parameters, which were used in the robustness analysis previously, influences the technology benefits or drawbacks compared to each other regarding GHG emissions. Therefore, a sensitivity analysis was also carried out for the difference of yearly total emission of the EU2035 scenario and the full ICEV scenario, where the comparison base is the full ICEV scenario, just like in *Figure 9*. The calculated indicators in the sensitivity analysis are the extent of cumulated emission overshooting in CO_2_eq kt, the break-even time of cumulated emission in past years after the base year and the absolute difference of yearly total emissions in 2035. The typical negative GHG impact of BEVs due to higher production emissions is described by the overshooting and break-even time, as well as the extent and the timeframe. Whereas lower overshooting and early break-even means a less negative GHG emission impact of BEVs, the higher gap in 2035 results in a more positive impact, when BEV scenarios result in a lower yearly total emission. *Figure 13, Figure 14 and Figure 15* represent the result of the sensitivity analysis for the difference of yearly total emission of the EU2035 scenario and the full ICEV scenario. Higher average yearly mileage and ICEV fuel consumption result in a lower overshooting, shorter break-even and greater difference in total emissions in 2035, meaning markets with high vehicle use and high mileage could have a better impact on GHG emissions by BEVs. The production emissions of BEV show a very high effect on overshooting; a 10% reduction results in 38% lower overshooting and 17% shorter break-even. Background calculations with higher factors show that a reduction of battery production emissions by 70%, which corresponds to 21 kg CO_2_eq/kWh battery production emissions, results in there being no overshooting at all. A similar calculation shows that +310% higher yearly average mileage, corresponding to 27,661 km, eliminates the overshooting as well.

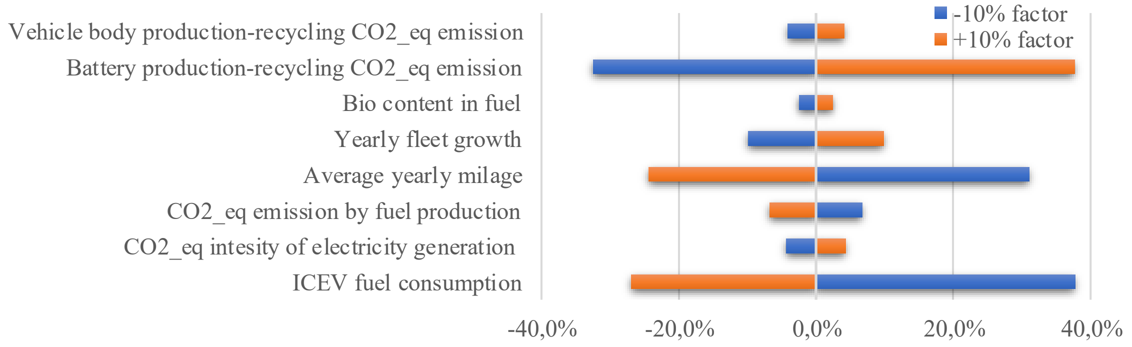

Figure 13 – Variation of the cumulated yearly total GHG emission overshooting by the EU2035 scenario compared to the full ICEV scenario

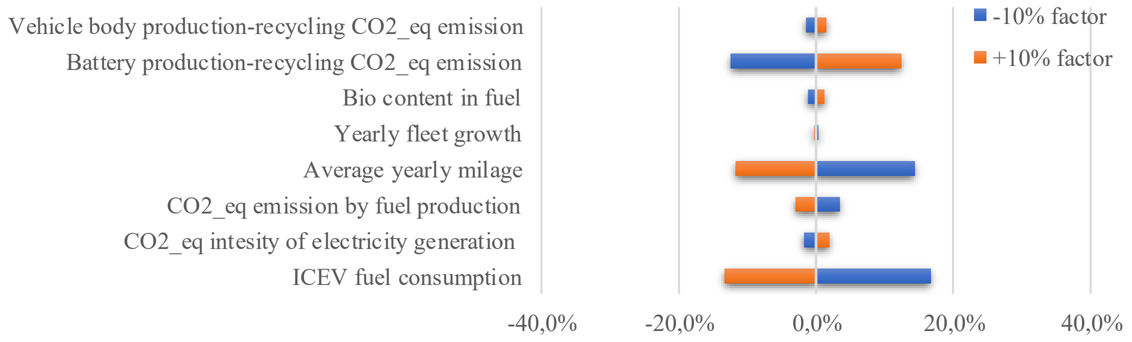

Figure 14 – Variation of the cumulated yearly total GHG emission break-even by the EU2035 scenario compared to the full ICEV scenario

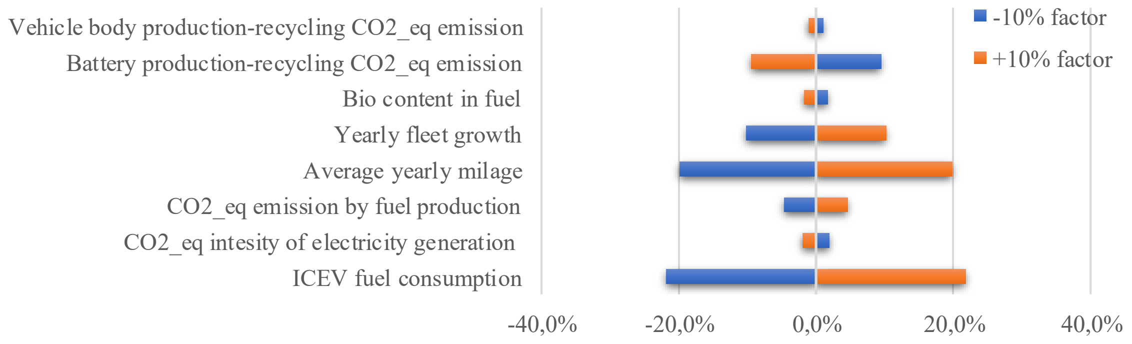

Figure 15 – Variation of yearly total GHG emission difference in 2035 between EU2035 and full ICEV scenarios

5. CONCLUSION

This study underscores the critical role that passenger car electrification plays in mitigating greenhouse gas emissions as societies worldwide confront the escalating impacts of climate change. By assessing the total CO_2 emissions from a fleet of passenger cars over a defined timeframe, we established a calculation method that incorporates real-world variables such as vehicle type distribution, average age, mileage and consumption. Consequently, the results have a good correlation to real GHG emissions as a base for the assessment of passenger car electrification. Our findings reveal that while the transition to BEVs presents short- and mid-term challenges, notably in production emissions and charging infrastructure, the long-term benefits are significant.

The model was applied to various projected scenarios, including edge cases such as the full ICEV scenario and the full BEV scenario, as well as the EU2035 scenario, which aligns with the European Union's ambitious climate goals. Under the EU2035 scenario, electrification begins to deliver net reductions after 2032, achieving a 5.3% annual decrease by 2035 compared to a full ICEV fleet. Sensitivity analysis identifies mileage, battery production, and fuel consumption as key drivers of environmental performance. These findings underscore the need for holistic strategies that address technology, infrastructure and regional conditions to ensure effective climate mitigation. Future research should incorporate upstream emissions from charging infrastructure and explore market-specific pathways for optimised electrification.

6. REFERENCES

[1] Méndez-Vallejo C, et al. *Climate change 2023: Synthesis report (full volume) contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change*. Intergovernmental panel on climate change; 2023. DOI: 10.59327/IPCC/AR6-9789291691647.

[2] *National emissions reported to the UNFCCC and to the EU under the governance regulation.* European Environment Agency. 2024. DOI: 10.2909/6331f651-8863-4656-a911-669f2a332a1e.

[3] Zöldy M, et al. Cognitive sustainability. *Cogn Sustain*. 2022;1(1). DOI: 10.55343/cogsust.7.

[4] Biró K, Szalmáné Csete M. Revealing the concept of sustainability in life cycle assessment. *Ecocycles*. 2023;9(2):49-58. DOI: 10.19040/ecocycles.v9i2.277.

[5] Szilágyi A, Bereczky Á. Az akkumulátoros elektromos személygépjárművek környezeti hatásainak értékelése a teljes életciklus figyelembevételével – hol az igazság? [Environmental impact evaluation of battery electric passenger vehicles considering the whole life-cycle – where is the truth?]. *Magyar Tudomány*. 2021;182(3). DOI: 10.1556/2065.182.2021.3.2.

[6] Yan W, et al. Assessing the environmental benefits of passenger cars electrification in metropolises: A case study of Singapore. *Int J Sustain Transp*. 2024;1-13. DOI: 10.1080/15568318.2024.2421840.

[7] Maglić L, Krljan T, Grubišić N, Maglić L. Estimating urban road transport vehicles emissions in the Rijeka city streets. *Promet Traffic Transp.* 2021;33(2):165-178. DOI: 10.7307/ptt.v33i2.3613.

[8] Mintzia D, Kehagia F, Tsakalidis A, Zervas E. A methodological framework for the comparative analysis of roadway and railway transport. *Promet Traffic Transp*. 2018;30(6):721-731. DOI: 10.7307/ptt.v30i6.2804.

[9] Burchart-Korol D, et al. Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic. *Journal of Cleaner Production*. 2018;202:476-487. DOI: 10.1016/j.jclepro.2018.08.145.

[10] Rinawati DI, et al. Potential for reducing CO2 emissions from passenger cars in Japan by 2030 to achieve carbon neutrality. IATSS Res. 2023;47(2):185-195. DOI: 10.1016/j.iatssr.2023.02.004.

[11] Faria R, et al. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. *Renewable and Sustainable Energy Reviews*. 2013;24:271-287. DOI: 10.1016/j.rser.2013.03.063.

[12] Vipartas T, Rimkus A, Zöldy M. Overview of problematic aspects of passenger car hybrid technologies. In: Prentkovskis O, Yatskiv I, Skačkauskas P, Junevičius R, Maruschak P. (eds). *TRANSBALTICA XII: Transportation Science and Technology.* Vilnius , Lithuania. 2022. DOI: 10.1007/978-3-030-94774-3_35.

[13] Lerchner I. Application of cognitive mobility approach in highlighted areas. In: *Zöldy M (ed.). Proceedings of the 3rd cognitive mobility conference. COGMOB 2024. Lecture notes in networks and systems.* 1258, Springer, Cham. 2025. DOI: 10.1007/978-3-031-81799-1_35.

[14] *Hungarian central statistical office*. https://www.ksh.hu/

[15] *European Union alternative fuel infrastructure regulation (AFIR*). International council on clean transportation. https://theicct.org/publication/afir-eu-april2023/

[16] Tomaszewska A, et al. Lithium-ion battery fast charging: A review. *eTransportation.* 2019;1:100011. DOI: 10.1016/j.etran.2019.100011.

[17] Kawamoto R, et al. Estimation of CO2 emissions of internal combustion engine vehicle and battery electric vehicle using LCA. *Sustainability.* 2019;11(9):2690. DOI: 10.3390/su11092690.

[18] *Monitoring of CO2 emissions from passenger cars – Regulation (EU) 2019/631*. European Environment Agency. https://co2cars.apps.eea.europa.eu/

[19] Tsiakmakis S, et al. *From NEDC to WLTP: Effect on the type-approval CO2 emissions of light-duty vehicles.* Luxembourg: Publications office of the European Union; 2017. DOI: 10.2760/93419.

[20] *Commission report under Article 12(3) of Regulation (EU) 2019/631*. Brussels: European Commission; 2024. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52024DC0122
[21] *Implementing decision 2023/1623. European Union*. https://eur-lex.europa.eu/eli/dec_impl/2023/1623/oj
[22] *Hungarian Energy and Public Utility Regulatory Authority.* https://mekh.hu/
[23] *Hungarian Petroleum Association. Statistics of motor fuel.* http://petroleum.hu/dokumentumok/uzemanyag-statisztikak/
[24] *Commission staff working document under Article 12(3) of Regulation (EU) 2019/631*. Brussels: European Commission; 2024. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52024SC0059
[25] Prussi M, et al. *JEC Well-To-Wheels report v5.* Luxembourg: Publications office of the European Union; 2020. DOI: 10.2760/100379.
[26] Steinmetz MFA, van Eijk E, Ligterink NE. *Real-world fuel consumption and electricity consumption of passenger cars and light commercial vehicles 2023*. Den Haag: TNO; 2024. https://resolver.tno.nl/uuid:f5f550d6-7d17-44db-965a-0a3e7c845a46
[27] *Greenhouse gas emission intensity of electricity generation, country level. European Environment Agency*. https://www.eea.europa.eu/
[28] *National Energy and Climate Plan of Hungary*. 2023. https://kormany.hu/
[29] Hao H, et al. Comparing the life cycle greenhouse gas emissions from vehicle production in China and the USA: Implications for targeting the reduction opportunities. *Clean Technol Environ Policy*. 2017;19(5):1509-1522. DOI: 10.1007/s10098-016-1325-6.
[30] Ambrose H, et al. Trends in life cycle greenhouse gas emissions of future light duty electric vehicles. *Transp Res D Transp Environ.* 2020;81:102287. DOI: 10.1016/j.trd.2020.102287.
[31] Lavigne Philippot M, et al. Eco-efficiency of a lithium-ion battery for electric vehicles. *Batteries*. 2019;5(1):23. DOI: 10.3390/batteries5010023.
[32] *All electric vehicles in Europe – EV Database.* https://ev-database.org
[33] Jungmeier G, Meltzer A, Beermann M. Estimated greenhouse gas emissions and primary energy demand of passenger vehicles – 3rd ed. *Green NCAP*; 2024. https://www.greenncap.com/test-procedures/
[34] Buberger J, et al. Total CO2-equivalent life-cycle emissions from commercially available passenger cars. *Renew Sustain Energy Rev*. 2022;159. DOI: 10.1016/j.rser.2022.112158.