Life Cycle Assessment of Energy Sources for Electric and Hydrogen Vehicles in Europe

Volodymyr Tymofiiv [1], Peter Korba [1], Samer Al-Rabeei [1], Juraj Horkay [1]

[1] *Technical University of Kosice, Faculty of Aeronautics, Kosice, Slovakia*

Abstract **– The progress of the European Union in achieving its environmental and climate goals is being hampered by rising oil consumption and greenhouse gas emissions. The EU transport sector remains heavily dependent on fossil fuels, which account for a quarter of greenhouse gas emissions in Europe, and this figure is constantly rising. There are several alternatives that can replace traditional vehicles, but only two of them have no direct CO2 emissions and are among the best in terms of environmental friendliness: the battery electric vehicle and the fuel cell electric vehicle. This article analyses greenhouse gas emissions from existing electricity and hydrogen generation in the European Union by source. The authors compare emissions from different types of vehicles and show how changes in the country's energy mix affect these emissions. In the practical part, AFLEET is used to better compare the information obtained with each other.**

Keywords **– BEV, FCEV, CO2 emissions, energy efficiency.**

1. Introduction

One of the most important treaties governing states and international environmental organizations is the Paris Agreement adopted under the UN Framework Convention on Climate Change in 2015.

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Corresponding author: Volodymyr Tymofiiv,
Technical University of Kosice, Faculty of Aeronautics, Kosice, Slovakia
Email: volodymyr.tymofiiv@tuke.sk

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The Paris Agreement aims to keep the increase in global average temperature well below 2°C above pre-industrial levels, while at the same time making efforts to limit the temperature increase to 1.5° [1].

To achieve this strategic goal, countries are striving to peak global greenhouse gas emissions as soon as possible to reach climate neutrality by the middle of the 21st century.

In addition to the Paris Agreement, several other agreements have been signed which set out the European Union's objectives in more detail. The best known of these are the European Green Deal, Fit for 55, Repower EU and others. Strategies to achieve these goals in specific regions or countries, which are drawn up by the countries themselves, also play an important role [2].

The development of electric batteries and hydrogen energy will play an important role in reaching climate goals. Batteries and hydrogen are also part of the vision for the future in Europe and other countries seeking to reduce CO2 emissions. It is estimated that the use of hydrogen could potentially reduce up to 51% of global carbon dioxide emissions [3].

Globally, there is growing concern about greenhouse gas emissions and dependence on cars, internal combustion engines and fossil fuels. However, despite many initiatives, urban mobility, including logistics, is still heavily dependent on fossil fuels and modal shift can be economically and socially challenging [4].

Motor vehicles powered by hydrocarbon fuels are responsible for 31.3% of carbon dioxide emissions in the EU (Figure 1) [5], making the transport sector the most CO2-intensive sector in Europe. The global vehicle fleet is also expected to double by 2050 compared to the beginning of the century, especially in urban areas which already suffer from air pollution. On average, transport accounts for more than 50% of the emissions that lead to air pollution at local and regional level [6].

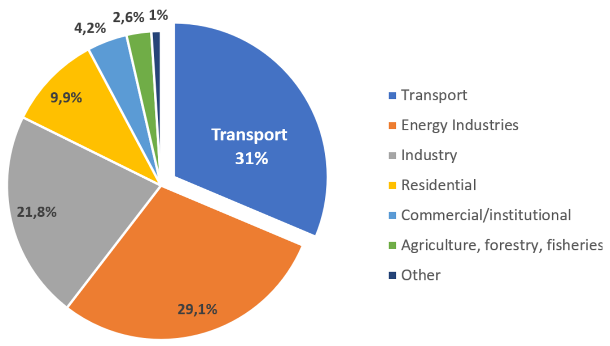

Figure 1. Distribution of carbon dioxide emissions in the European Union in by sector(in million metric tons of CO2 equivalent)*
(Source: own elaboration, data from www.statista.com)

In the road transport sector, passenger cars have the highest emissions (41%) due to their large number compared to other transport modes (Figure 2) [7].

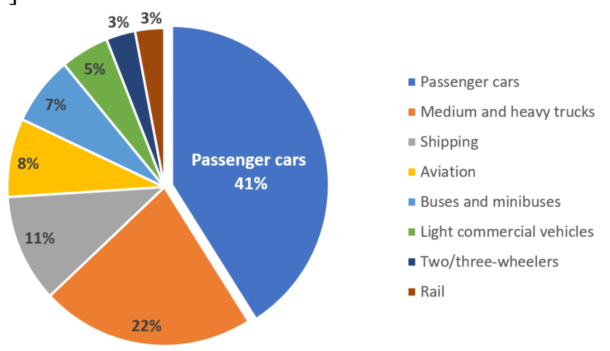

Figure 2. Distribution of carbon dioxide emissions produced by the transportation sector worldwide by subsector
(Source: own elaboration, data from www.statista.com)

In the European Union, there are on average 560 passenger cars and around 81 commercial vehicles and buses per 1 000 inhabitants. This is more than 1 car for 2 people. As of 2020, among the countries of the European Union, the highest car density is observed in Luxembourg (696 per 1000 inhabitants) and the lowest in Latvia (353).

The road transport sector together accounts for around 70% of all emissions in the transport sector, or 21.7% of emissions across all sectors in the EU. The remaining 30% of emissions come from rail, air, and maritime transport. This means that it is the decarbonisation of the road transport sector that needs to be targeted to maximize the overall effectiveness of measures [8].

The negative environmental and public health impacts are much smaller for rail transport, including high-speed lines and urban electrified transport. On this basis, it can be said that the introduction of more electrified trains, trams and electric buses can already reduce CO2 emissions [9].

2. Methodology

The methodology adopted in this study aims to provide a holistic assessment of the life cycle of greenhouse gas emissions (GHG) associated with different vehicle technologies. By incorporating different energy sources and realistic scenarios, the study provides valuable information on the environmental benefits and drawbacks of each vehicle type, helping to inform decisions towards a more sustainable transport future [10], [11].

The study includes a wide range of vehicle technologies, including internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and fuel cell electric vehicles (FCEV). This allowed us to compare in detail the environmental performance of different powertrain configurations and to understand the extent to which the use of alternative fuels can replace fossil fuels.

The analysis went beyond the vehicles themselves, delving into the environmental impacts of the energy sources that power them. Fossil fuels (coal, natural gas, oil fuels) were assessed alongside renewable energy sources. In addition, the study examined two different methods of hydrogen production - steam methane reforming (SMR) and electrolysis - to understand their different environmental impacts.

To take into account the significant impact of the energy source on the overall environmental impact, three different scenarios were modelled:

(a) Fossil fuel dependence: this scenario assumed electricity generation from fossil fuels and hydrogen production from SMR, which means dependence on traditional energy sources with high emissions.

(b) Renewable energy dominance: This scenario envisaged a future based on 100% renewable energy sources for electricity generation and hydrogen production through electrolysis, reflecting a transition to a sustainable energy landscape.

(c) European average energy mix: this scenario reflects the current reality in the European Union by using an average energy mix for electricity generation and including a single value for hydrogen emissions (either SMR or electrolysis), recognising the limitations in data availability.

The AFLEET tool was used to model emissions in the study. This is a tool for estimating GHG emissions for each vehicle type under different scenarios. AFLEET includes data on a vehicle's fuel consumption, energy sources used, and annual mileage to produce these estimates [12]. To create a more complete picture, information on the current average energy consumption balance in the European Union, as well as data on the balance of individual countries, was used for the scenario analysis.

It should also be noted that the AFLEET tool was originally developed for the US market, and although the parameters have been adjusted for the EU, there may be slight inaccuracies in the results for European vehicles.

3. The Ecology of Electricity in the EU

BEVs and FCEVs emit almost no direct emissions during use. This advantage allows emissions to fall in large cities, which means fewer illnesses related to a poor environment and this generally improves people's health. It will also help get rid of acid rain and smog in big cities. These few facts alone are a huge benefit for BEVs and FCEVs, especially for metropolises with more than 100,000 vehicles [13].

In addition to direct air pollution, cars with internal combustion engines also create noise pollution. Long-term exposure to environmental noise leads to 12 000 premature deaths a year in Europe and contributes to 48 000 new cases of coronary heart disease, and 6.5 million people suffer from severe chronic sleep disorders. In addition, noise also has a negative impact on terrestrial and aquatic wildlife.

BEV and FCEV engines are almost completely silent and contribute much less to noise pollution than internal combustion engines [14].

Although their use generates only minimal pollution, greenhouse gas emissions are generated at other stages. In fact, we are not getting rid of emissions, we are just moving them from where the cars use the energy to where it is produced. This undoubtedly has its advantages, as it will be easier to equip existing power generation systems, such as coal or gas-fired cogeneration plants, with the right filters or to introduce CCUS (Carbon Capture, Utilization, and Storage). At the same time, the climate impact is still large, as emissions from BEVs and FCEVs (hydrogen produced by electrolysis) depend directly on the greenness of the electricity generation method (Figure 3) [15].

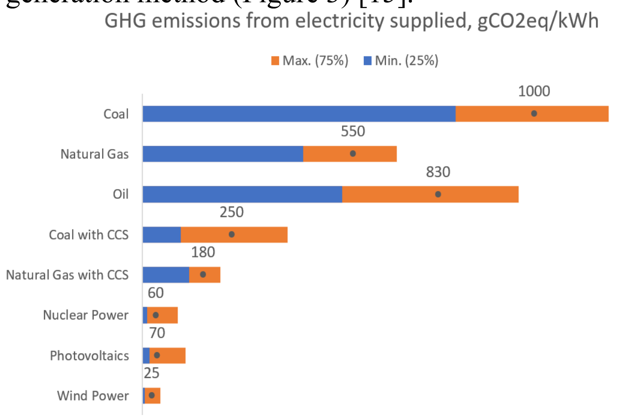

Figure 3. Comparative lifecycle greenhouse gas emissions from electricity supplied by commercially available technologies (from 20% to 80%)
(Source: own elaboration, data from www.eea.europa.eu)

The above graphs show that most greenhouse gases are produced when the source of electricity is coal and there are approximately 1000 grams of carbon dioxide per 1 kW/h of energy produced (range - 775-1689 [gCO2 eq/kWh]). The corresponding ranges for oil and gas were 510-1170 [gCO2eq/kWh] and 290-930 [gCO2eq/kWh] respectively. The ranges of possible emissions are generally quite broad and reflect differences in local conditions, technology and methodological choices in the assessment [16]. The lower end of the estimates often reflects incomplete systems, while the upper end reflects poor local conditions or outdated technologies. Although renewable energy has no direct CO2 emissions to the atmosphere, emissions are generated, for example, by the manufacture of solar panels, their installation and disposal.

Assuming an average BEV consumes 20 kWh of energy per 100 km (ranging from 15 kWh to 35 kWh per 100 km depending on conditions, vehicle make and driving type [17]), emissions from BEVs using electricity from coal-fired power plants will be 20,000 gCO2eq per 100 km or 200 gCO2eq per 1 km. This calculation does not consider the energy consumption during transport and when charging the battery [18].

At the same time, vehicle manufacturers have introduced emission limits for new cars in the form of a maximum allowable emission of 95 grams of carbon dioxide per kilometer, measured according to NEDC data [19]. Nevertheless, new cars sold in the EU in 2021 had an average CO2 emission of 114.1 g CO2-eq/km (10% of new cars sold were BEVs and 9% were HEV/PHEVs). According to various sources, ICEV emissions range from 140-180 CO2-eq/km, while emissions from older ICE cars can exceed 250 gCO2eq/km. Thus, ICEVs emit an average of 16,000 gCO2eq per 100 km, or 160 gCO2eq/km. These are direct emissions and do not include the full life cycle emissions [20].

The climate impact of an electric car is then proportionally higher compared to a conventional car. However, this rule only applies to a few small regions where most of the electricity is generated by old coal-fired power stations. Countries with the highest share of electricity generated from coal and other grey sources include Poland - 736 [gCO2eq/kWh] (74.5% of the country's energy comes from coal-fired power plants [21]), Estonia - 693 [gCO2eq/kWh] and Cyprus - 599 [gCO2eq/kWh]. Among the countries with the lowest CO2 emissions per kW produced, Sweden leads with 10[gCO2 eq/kWh], Luxembourg with 55[gCO2 eq/kWh] and France with 58[gCO2 eq/kWh (Figure 4) [22].

Therefore, Sweden is the leader in EV sales, with EVs accounting for 45% of passenger car registrations in the country in 2021. In general, the average emission value in the European energy mix is 261 [gCO2 eq/kWh].

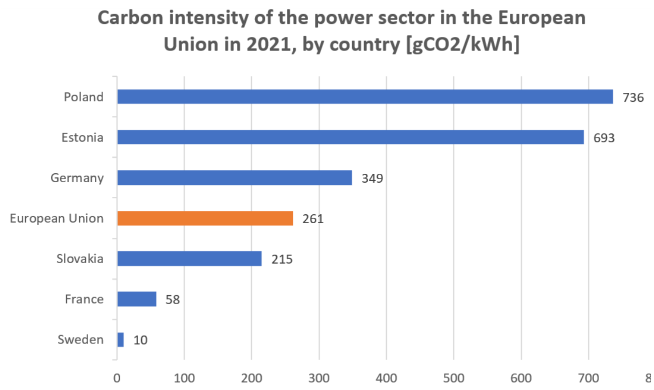

Figure 4. Carbon intensity of the power sector in the European Union in 2021, by country [gCO2/kWh] (Source: own elaboration, data from www.statista.com)

In addition to analysing the EU's current fuel mix, it is worth saying a few words about its future. As we have recalled, Europe is moving towards full decarbonisation of all its sectors, and renewables are expected to help it achieve this. The EU plans to increase current renewable energy capacity by 40% by 2030. This suggests that the use of BEVs and FCEVs will eventually be even greener than it is today [23].

4. The Environmental Friendliness of Hydrogen Use

The sustainability of hydrogen production is often discussed, especially in the context of fuel cell electric vehicles (FCEVs). Although hydrogen has the advantage of producing only water as a byproduct during combustion, the process of its production can have a significant impact on the environment and is highly dependent on the source of its creation Therefore, we need to consider the source from which we get the hydrogen to use, as less than 5% of low-carbon hydrogen is currently on the market [24].

The most common method of hydrogen production is steam methane reforming (SMR), which involves the reaction of methane with steam at high temperatures and pressures. This process releases a significant amount of carbon dioxide. On average, 9.3 kilograms of CO2 are emitted per kilogram of hydrogen produced by SMR.

Coal gasification, another common method of hydrogen production, is even more carbon-intensive, emitting approximately 18.6 kilograms of CO2 per kilogram of hydrogen. This method involves reacting coal with steam to produce synthesis gas, which is then converted to hydrogen.

The significant carbon emissions associated with coal gasification pose a significant environmental problem (Figure 5) [25].

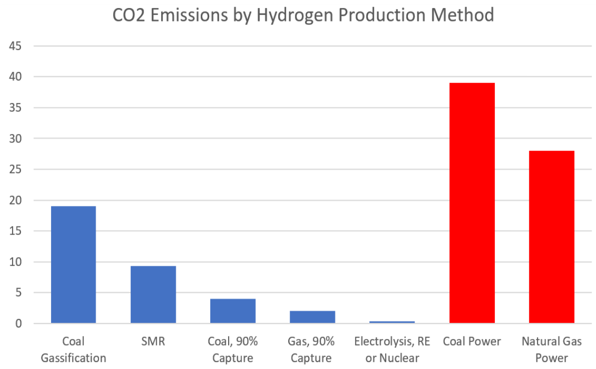

Figure 5. CO2 emissions by hydrogen production method. RE - renewable energy. SMR - steam methane reforming. (Source: own elaboration, data from www.iea.org)

Emissions from both processes will be significantly reduced by CCUS, but it will increase the production cost of hydrogen and there are several technological reasons and constraints for using CCUS [26].

However, if hydrogen is produced using electricity from renewable or nuclear sources, such hydrogen will have virtually no CO2 emissions and will only be generated by the production or use of infrastructure. However, if electricity from fossil fuels is used to produce hydrogen, emissions will increase many times over, and a kilogram of hydrogen from coal-fired electricity will cause emissions of up to 40 kg CO2/kgH2 [27].

Since a hydrogen vehicle has an average consumption of 1 kg of hydrogen per 100 km, the CO2 emissions from the SMR will be 9300 gCO2 /100 km or 280 gCO2/kWh (a kilogram of hydrogen has an energy density of 33.33 kWh), which can be considered a good result compared to the emissions from natural gas for power generation (550 gCO2 eq/kWh) [28].

5. Using the AFLEET to Calculate Greenhouse Gas Emissions in Different Energy Source Scenarios

The authors have been using and testing the AFLEET (Alternative Fuel Life Cycle Environmental and Economic Transportation) tool to obtain data on vehicle emissions under various energy use scenarios. The data obtained are successive graphs generated by the AFLEET tool based on the number of vehicles, annual kilometrage, energy sources, and more.

Figure 6 presents start window of the AFLEET with certain settings.

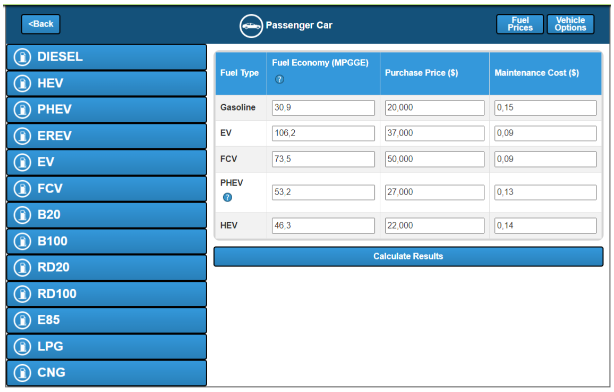

Figure 6. AFLEET interface
Source: own elaboration in the AFLEET tool © Argonne National Laboratory

Although all possible parameters have been replaced by European Union parameters, this instrument is designed with the US market in mind. Therefore, the results obtained may differ slightly from the actual results for the EU. Also, these results have been converted by the authors from the English to the metric system.

Since this tool has been adjusted to the specification of the American market, the results for Europe may have some inaccuracy. Also the output results are given in the imperial system and are later converted to the metric system.

The tool uses data from the Greenhouse Gas Fuel Cycle, Regulated Emissions and Energy Use in Technology (GREET) models to calculate the required oil consumption and GHG emission factors for major production routes and vehicle types. The program also has average Fuel Economy (MPGGE) and Purchase Price data for each vehicle type. Since this tool was developed with the US market in mind, the results may differ slightly from the actual results for the EU.

The study analyzed 5 types of passenger cars in this simulation:

- Internal Combustion Engine vehicle (ICE) powered by gasoline.
- Hybrid Electric Vehicles (HEV).
- Plug-in Hybrid Electric Vehicles (PHEV).
- Electric Vehicle (EV) / Battery Electric Vehicle (BEV.)
- Fuel Cell Vehicle (FCV) or Fuel Cell Electric Vehicle (FCEV).

These types of vehicles were analyzed in 3 different situations depending on the source from the energy (Figure 7):

1. the use of electricity from fossil sources (75% coal, 25% natural gas, 5% Residual Oil) as well as hydrogen produced from methane by the SMR (steam methane reforming) method (Figure 7a):
2. use of electricity from 100% renewable energy sources and hydrogen produced by electrolysis (Figure 7b).
3. European fuel mix (Figure 7c) [29].

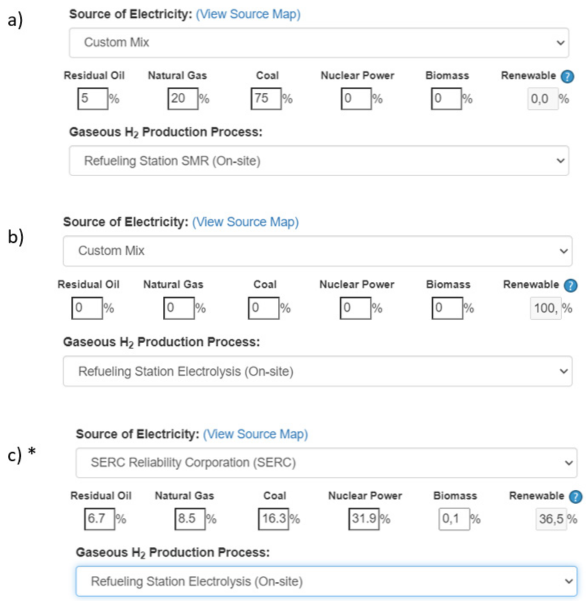

Figure 7. Sources of electrical energy
a) the use of electricity from fossil sources (75% Coal, 20% Natural Gas, 5% Residual Oil) as well as hydrogen produced from methane by the SMR (steam methane reforming) method
b). use of electricity from 100% renewable energy sources and hydrogen produced by electrolysis.
c). European fuel mix (Data from op.europa.eu)
(Source: own elaboration in AFLEET tool © Argonne National Laboratory)

The average annual number of kilometers driven by car in Europe in 2022 was 11,300 km [30]. The information is used in calculations.

6. Results

The results of our simulation are shown in Figures 8, 9, and 10.

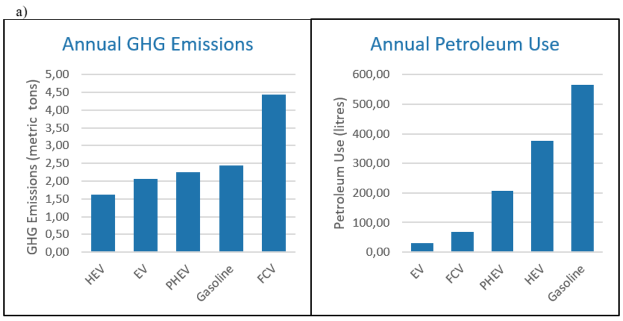

Figure 8. Annual GHG emissions and petroleum use of electricity from 100% fossil sources mix
(Source: own elaboration in AFLEET tool © Argonne National Laboratory)

b)

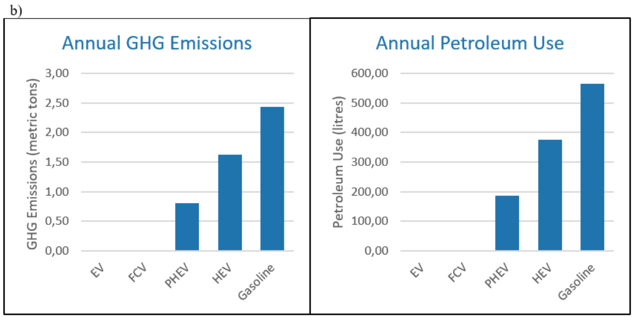

Figure 9. Annual GHG emissions and petroleum use of electricity from 100% renewable energy
(Source: own elaboration in AFLEET tool © Argonne National Laboratory)

c)

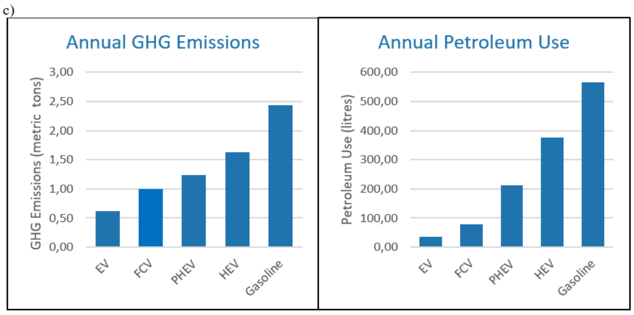

Figure 10. Annual GHG emissions and petroleum use of electricity from European fuel mix.
(Source: own elaboration in AFLEET tool © Argonne National Laboratory)

Annual GHG emission shows how much a vehicle emits in 1 year of CO2 equivalent greenhouse. In the case of using hydrogen obtained by SMR (a), the GHG emission level will be the highest and there will be no benefit from the decarbonisation process. Similarly, electricity generated solely from fossil fuels would have almost no positive impact on total emissions. In this scenario, HEV has the best results, meaning that its use makes the most sense in countries with high CO2 emissions per m2/year of energy produced.

In the second scenario (b), the electricity is obtained exclusively from renewable energy sources and therefore BEVs and FCEVs are emission-free in terms of energy consumption. In the case of FCEVs, a certain amount of greenhouse gases may be emitted during transport. In the case of PHEVs and HEVs it can be seen that the amount of emissions is directly related to the proportion of electricity used in the vehicle.

In the case of PHEVs, it has to be said that it is very difficult to make accurate calculations of greenhouse gas emissions because this mode of transport is more dependent on the driving style of its owner than any other. Therefore, it turns out that the best emission values for PHEVs are shown for frequent use of the internal combustion engine, in the case with a poor CO2 balance in the energy mix, and for frequent use of the electric motor and batteries, in the case with a good CO2 balance.

The third option (c) shows the European average for passenger car emissions in the European Union pointing out that emissions from BEV use would also be the lowest in the case of energy in the overall energy mix. In the case of FCEVs, everything will depend on how the hydrogen is produced. Since its use of SMR does not make much sense if it is produced from renewable energy sources, it can have the lowest emission values, only in this case the feasibility of this process is already in question.

Only one value (SMR or electrolysis) can be determined and therefore an exact figure cannot be assumed, but from the results of a and b it can be said that the minimum value of emissions from hydrogen production will be 0.3 tons per year and this value will increase when SMR is used for FCEVs.

Annual petroleum use shows how much petrol a vehicle uses in a year. In the case of BEVs, the amount of petrol used is directly related to its share of the country's energy mix. In the case of FCEVs, petrol is consumed, for example, when transporting hydrogen or when hydrogen is produced by electrolysis using electricity from the grid. Then, as in the case of BEVs, the amount of petrol used will depend on its value in the energy mix.

7. Conclusion

This article discussed the environmental friendliness of producing two fuels to power an electric motor: electricity and hydrogen. The authors also compared the emissions of BEVs and FCEVs with conventional internal combustion engine vehicles. In the practical part, additional HEVs and PHEVs are added to the comparison to see how the greenness of the vehicle varies with the size of the battery.

The results:

1. In terms of environmental performance, electric vehicles emit less greenhouse gases than conventional cars in most EU countries. But even if emissions were the same, BEVs would have a big advantage in that emissions would be shifted away from populated areas.
2. Hydrogen makes sense in the case of blue hydrogen as a low-carbon mode of transport, but only completely green hydrogen created by electrolysis from renewable sources can be completely green. Electrolysis from other energy sources leads to the highest emissions compared to all other cases.
3. If BEVs and FCEVs receive the same amount of energy from renewable energy sources, the BEV will be greener because it has fewer losses in the Willis Towers Watson (WTW) chain and needs less energy to operate.

4. In countries with a large share of electricity from fossil fuels, HEVs will be the most environmentally friendly, while BEVs will be the most environmentally friendly in the case of RES.

The conclusions of this article will help to better understand the greenhouse gas emissions that are produced when different types of vehicles are in use. The authors have tested the AFLEET vehicle emissions assessment tool and perhaps the experience will bring further insights to this environment.

The topic of decarbonising road transport will also be relevant in the future, as the targets of the various climate agreements are very ambitious and there are still many challenges to be addressed on the way to achieving them.

Acknowledgements

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