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The Environmental Impacts of Future Global Sales of Hydrogen Fuel Cell Vehicles

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Abstract: During the last decade, developing more sustainable transportation modes has become a primary objective for car manufacturers and governments around the world to mitigate environmental issues, such as climate change, the continuous increase in greenhouse gas (GHG) emissions, and energy depletion. The use of hydrogen fuel cell technology as a source of energy in electric vehicles is considered an emerging and promising technology that could contribute significantly to addressing these environmental issues. In this study, the effects of Hydrogen Fuel Cell Battery Electric Vehicles (HFCBEVs) on global GHG emissions compared to other technologies, such as BEVs, were determined based on different relevant factors, such as predicted sales for 2050 (the result of the developed prediction model), estimated daily traveling distance, estimated future average global electricity emission factors, future average Battery Electric Vehicle (BEV) emission factors, future global hydrogen production emission factors, and future average HFCBEV emission factors. As a result, the annual GHG emissions produced by passenger cars that are expected to be sold in 2050 were determined by considering BEV sales in the first scenario and HFCBEV replacement in the second scenario. The results indicate that the environmental benefits of HFCBEVs are expected to increase over time compared to those of BEVs, due to the eco-friendly methods that are expected to be used in hydrogen production in the future. For instance, in 2021, HFCBEVs could produce more GHG emissions than BEVs by 54.9% per km of travel, whereas in 2050, BEVs could produce more GHG emissions than HFCBEVs by 225% per km of travel.

Keywords: global passenger car sales; global GHG emissions; hydrogen fuel cell vehicles; sustainable transportation; FCEVs; electric vehicles; BEVs; HFCBEV

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1. Introduction

Recently, the development of more sustainable vehicle technologies has become one of the main approaches used to overcome challenges related to greenhouse gas (GHG) emissions and climate change. Fossil fuel is still the predominant source of energy in the global transport sector, generating 37% of global carbon dioxide (CO_2) emissions from the transport sector [1]. During 2022, the rebound in cargo and passenger activities following the coronavirus pandemic led to a 3% increase in the CO_2 emissions produced by the transportation sector compared to the previous year [2], which counted nearly 7.7 Gt-CO_2 emissions from the transportation sector [3,4]. Transport sector-related emissions grew at an annual average rate of 1.7% from 1990 to 2022, faster than any other end-use sector, except for industry, which had almost the same rate [2].

Different vehicle technologies have been developed over the last two decades to decrease the dependence on fossil fuels and mitigate the related environmental issues. These technologies can be divided into the following main categories: Battery Electric Vehicles (BEVs), which are powered by traction batteries and electric motors; Hybrid Electric Vehicles (HEVs), which are powered by electric motors and internal combustion engines; Plug-in Hybrid Electric Vehicles (PHEVs), which are mainly considered as Hybrid Electric Vehicles with the ability to recharge the battery using a power grid; and Hydrogen Fuel Cell Batter Electric Vehicles (HFCBEVs), which are electric vehicles with fuel cells powered by hydrogen as a source of electricity.

However, while BEVs emit zero emissions on board or with no tailpipe, there are still emissions produced in power plants in order to provide the required electricity for vehicle operation. Moreover, BEVs suffer from major drawbacks, such as a limited range and a long charging time, which may take several hours when using home power sources. However, these drawbacks and limitations have been addressed by developing the HFCBEV, which can be refueled by hydrogen within a few minutes and has an extended range [5].

HFCBEVs use a system that is operated by electrical energy engendered by a battery and a fuel cell, instead of relying only on a battery to provide the required power. Thus, the magnitude of the hydrogen tank determines the amount of energy delivered, and as a result, a longer range can be obtained [6,7]. The battery provides the car with a considerable power, in addition to braking energy recycling, while the hydrogen fuel cell is considered a superior energy source that charges the battery in order to extend the range of the vehicle. In this system, the hydrogen fuel cell is considered a chemical reactor [5]. Therefore, HFCBEVs should be refueled with hydrogen instead of fossil fuel or grid electricity, which can be classified into different categories based on its production method—gray, blue, and green hydrogen.

The technology used in HFCBEVs is considered to be one of the most promising technologies in the field of transportation sustainability, and the effects of this technology on global GHG emissions compared to BEVs should be investigated in the short and long terms. This study aims to determine the expected global passenger car sales in 2050 and to investigate the effects of HFCBEV sales on global GHG emissions compared to BEVs in the long term (in 2050), based on different estimated factors, such as the future global hydrogen and electricity consumption rate of vehicles, estimated future average global electricity emission factors, future average BEV emission factors, future global hydrogen production emission factors, and future average HFCBEV emission factors.

2. Literature Review

The use of hydrogen fuel cells as an alternative source of energy in the transportation sector is considered a promising technology, and the impact of this technology has been investigated by numerous studies over the last 10 years by considering the different aspects of use and various local factors. However, it still has a low user acceptance compared to internal combustion engine vehicles. One of these studies was conducted by Mendez et al. [8] to determine the advantages and disadvantages of various alternative vehicles, including HFCBEVs in Qatar and the Gulf Cooperation Council. The study concluded that out of eight alternative vehicles and based on different aspects such as performance, environment, market acceptance, and economy, HFCBEVs and PHEVs ranked first and second, respectively. Similarly, Hassouna and Shin [5] conducted a study to assess the environmental impact of HFCBEVs in Palestine. The expected environmental impacts of HFCBEVs in Westbank were investigated and compared to other technologies, such as HEVs and BEVs, and were based on factors such as average annual traveled kilometers and electricity and fuel sources. The study concluded that HFCBEV technology could be considered the most environmentally friendly alternative and could lead to a significant reduction in GHG emissions compared to BEVs and HEVs. Similarly, Ahmadi and Khoshnevisan conducted another study to assess the lifecycle of HFCBEVs [9]. Dynamic simulations were conducted using computer software, and various hydrogen production methods were considered. The results of the study concluded that a hydrogen vehicle with a degraded fuel cell produces less CO_2 than a gasoline vehicle, and the emitted CO_2 from this vehicle is approximately 25% greater than that of a new hydrogen vehicle. To analyze the technological life cycle of HFCBEVs compared to other propulsion modes (HEVs, ICEVs, and BEVs), Sinigaglia et al. conducted a study [10]. The data were collected on the Questel Orbit platform for patent families published in the US and Europe. After that, a proper model was developed, the level of technological maturity was evaluated for each of these technologies. The results of this study indicate that HFCBEV technology has reached technological maturity.

Focusing on different aspects, other studies investigated the implications of using HFCBEVs. Hassouna and Shin conducted one of these studies [6] to determine the economic prospects of using hydrogen fuel cell technology in taxi fleets. The results concluded that using hydrogen fuel cell technology is expected to become increasingly feasible over time due to the expected significant reduction in hydrogen production cost and the continuous increase in oil price. A study conducted by Rout et al. [11] investigated the cost competitiveness of HFCBEVs by analyzing the total cost of ownership. Assessments were performed for the present day (2021) scenario. Moreover, a future outlook was conducted by examining the impact of time-sensitive factors on the total cost of ownership when reaching net zero targets. Another study was conducted by Dulau [12] in order to determine the CO_2 emissions of BEVs and HFCBEVs. The analysis of this study considered different values for the mix of power generation and hydrogen production options in comparison to other studies. The results of the study concluded that the CO_2 emissions of BEVs are lower when compared to FCEVs if the hydrogen is obtained from pollutant sources, but are higher if the hydrogen is obtained from nuclear power and renewable energy sources. A study by Chi et al. [13] was conducted to assess the environmental and economic impacts of HFCBEVs in China. The study carried out a fuel-cycle analysis of HFCBEVs in 2020 and 2030 using the Greet model. The results of the study concluded that decreasing trends in both pollution emissions and the cost of HFCBEVs are expected towards 2030. Specifically, the CO_2, VOC, NO_X, $POM_{2.5}$, and SO_2 emissions would decrease by 21.58%, 16.55%, 22.35%, 22.49, and 18.76%, respectively.

In addition to passenger cars, commercial and heavy vehicles powered by fuel cells have also been studied to determine their expected drawbacks and benefits. In addition, Breuer et al. [14] investigated fuel cell electric vehicles, battery electric vehicles, and overhead catenary line trucks by considering their potential to reduce GHG emissions, air pollution, and the operating costs of the required infrastructure. A bottom-up transport model for the federal state of North Rhine, Germany was used. The study indicated that a comprehensive approach, such as fuel cell electric drives for all trucks, could be more beneficial. Similarly, Liu et al. conducted a study in China [15] to calculate the GHG emissions of Chinese heavy-duty truck fleets under four penetration scenarios from 2020 to 2050 (aggressive, conservative, moderate, and no fuel cell vehicle scenarios). The results indicated that the aggressive, moderate, and conservative HFCBEV scenarios can achieve 63%, 30%, and 12% reductions in GHG emissions, respectively, in 2050. A study by Munoz et al. [16] compared different urban bus fleet technologies based on three indices that determine the global warming potential in terms of CO_2-eq, emissions well-to-wheel energy use, and total ownership cost. The study indicated that the transition of the whole bus fleet into hydrogen fuel cell buses in Argentina could lead to a reduction of 1.3 Mt of CO_2-eq emissions.

Overall, the majority of previous studies have investigated the impacts of using HFCBEVs under local conditions (for specific countries or regions) and have mainly considered the current situation (short-term). Moreover, numerous studies have focused only on the performance and economic impacts. This study aimed to determine the effect of HFCBEV sales on GHG emissions on a global scale by considering the estimated global emission factors for HFCBEVs, BEVs, hydrogen, and electricity production in the long term (2050).

3. Data and Methodology

To determine the effects of HFCBEV future sales on global GHG emissions compared to other technologies, such as BEVs, global passenger car sales for the period 2005–2022 were used to develop a prediction model for future sales (2050). Next, the average daily travel distance, future global electricity emission factors, future BEV emission factors, future global hydrogen production emission factors, and future HFCBEV emission factors were estimated. Finally, the effects of HFCBEV global sales (in 2050) on GHG emissions were determined and compared to those of BEVs, as shown in Figure 1.

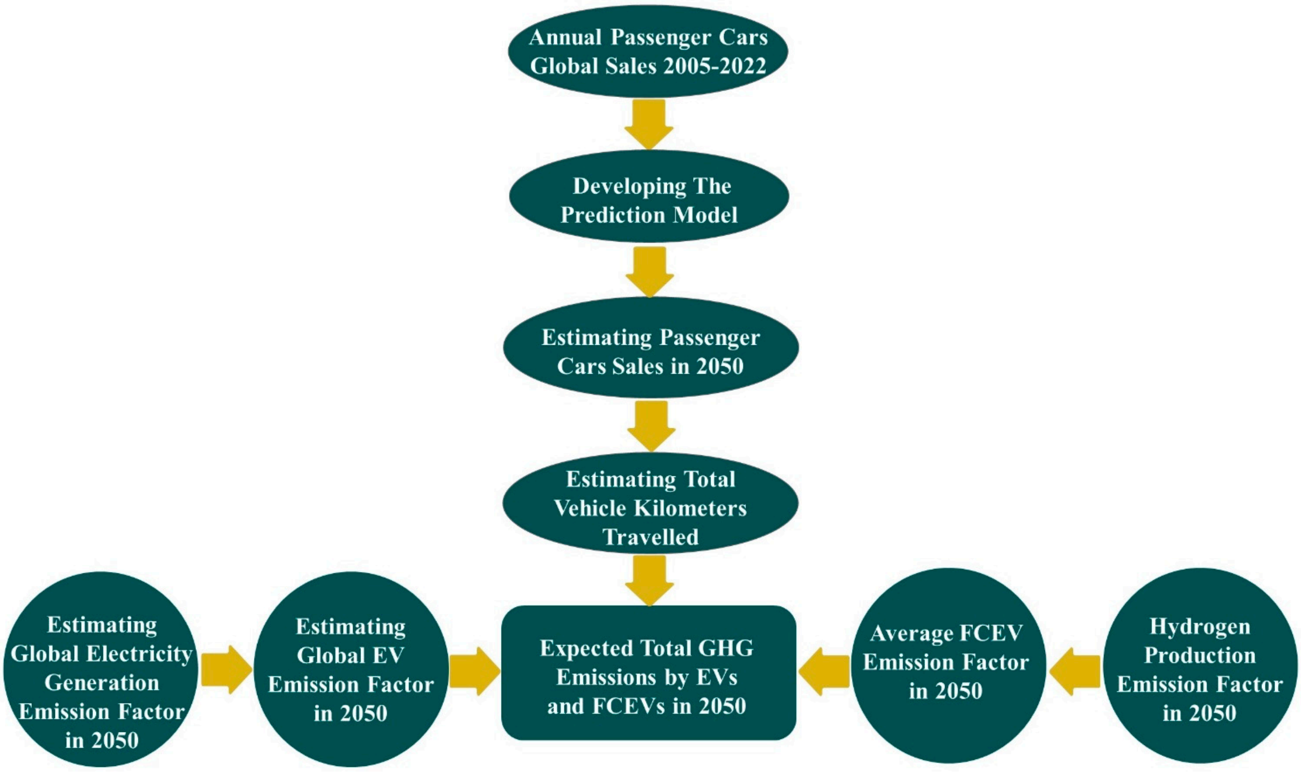

Figure 1. Research methodology flowchart.

Based on the historical global sales of passenger cars for the period 2005–2022, and using the exponential smoothing method, a prediction model was developed to estimate the expected number of passenger car global sales in 2050. It is worth mentioning that using a sample size of 15 for transportation-related prediction would be practical and would lead to reasonably accurate results. However, a larger sample size may lead to better results [17].

Exponential smoothing is a technique used to exponentially smooth the data in a time series over a period by assigning either exponentially increasing or decreasing weights to the values. Therefore, the recent data in the time series will have a greater effect on the predicted values than the farther-back data [18]. This method can be divided into three main categories, as follows: simple exponential smoothing, winter exponential smoothing, and Holt exponential smoothing. Based on the data used in this study, Holt's exponential smoothing was considered the most appropriate method for this type of data. Therefore, the Holt method was used in this study, as shown in Equation (1) [19].

$$\begin{gathered} F_{t+m} = s_t + m b_t \\ s_t = \alpha x_t + (1-\alpha)(s_{t-1} + b_{t-1}) \\ b_t = \beta(s_t - s_{t-1}) + (1-\beta) b_{t-1} \end{gathered} \tag{1}$$

where s_t is the smoothed value for year t, F is an estimate of the x value at time t + m, m is a value > 0, b_t is the best-estimated trend at year t, α is the smoothing factor ($0 < \alpha < 1$), x_t is the sequence of the data, and β is the trend factor ($0 < \beta < 1$).

Since HFCBEVs are mainly electric vehicles with a fuel cell that constitutes a source of electricity, it is considered the next generation of BEVs. In this study, the average of the top three countries in electric vehicle sales was considered in estimating the average daily driving distance, electricity generation emission factors, hydrogen production emission factors, average BEV emission factors, and HFCBEV emission factors. More specifically, the total electric vehicles sales in China, the United States, and Germany constitute more than 60% of the electric vehicle global sales [20].

The GHG emissions produced as a result of the global sales of HFCBEVs in 2050 were determined based on the estimated average hydrogen production emission factor (Kg CO_2-eq/kg); the average hydrogen consumption of HFCBEVs, which was estimated as the average value for different tested vehicles (kg/100 km); the average daily travel (km); and by considering the expected development in hydrogen production using more eco-friendly technology and the expected continuous future increase in the fuel efficiency of the new HFCBEVs that are manufactured over time.

Likewise, the GHG emissions produced as a result of BEVs' global sales in 2050 were determined based on the estimated average electricity generation emission factor (Kg CO_2-eq/kWh); the average electricity consumption of BEVs, which has been estimated as the average consumption for the passenger car models with the highest global sales; the average daily traveling distance (km); and by considering the expected future increase in renewable energy share in electricity grid sources and the expected future increase in the power efficiency of the BEVs due to the new technologies used in manufacturing the new vehicles. Finally, the GHG emissions produced by HFCBEVs that are expected to be sold in 2050 (as a replacement for BEVs) were determined and compared to the GHG emissions that are expected to be produced by BEVs (in the absence of FCEVs).

4. Data Analysis and Results

By using global passenger car sales records for the period 2005–2022 [21], the best-fit Holt's exponential smoothing model has been developed and the curve for the fit and observed values were drawn, as shown in Figure 2 and illustrated in Table 1 (prediction control limits), in order to predict the global sales of passenger cars in 2050, and to determine the GHG emissions produced as a result of these sales based on two scenarios (BEV and HFCBEV penetration), based on the future estimated emission factors for 2050 of electricity generation, hydrogen production, average fuel consumption of HFCBEVs, average electricity consumption of BEVs, and average daily traveling distance for passenger cars.

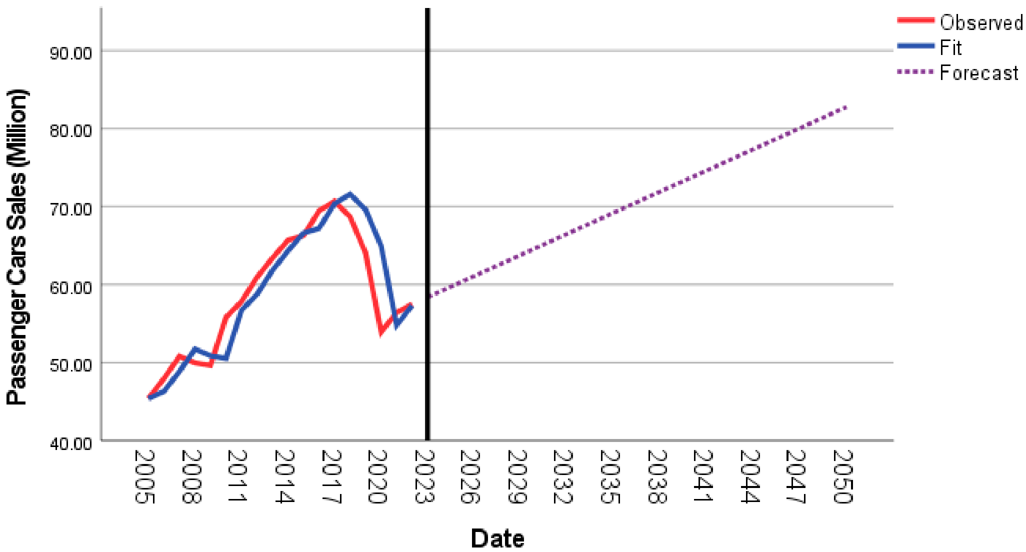

Figure 2. Observed and fit values for developed model.

Table 1. Prediction control limits.

Year	2025	2030	2035	2040	2045	2050
Upper Control Limits	73.77	86.90	97.55	107.12	116.04	124.52
Lower control Limits	46.63	42.53	40.91	40.38	40.49	41.05

As shown in Table 2, the R-Squared and Mean Absolute Percentage Error (MAPE) values for the developed model showed acceptable prediction accuracy. The MAPE, which is the sum of the individual absolute errors divided by the demand for the prediction model, has a value of 4.081 (a MAPE value < 5 is considered an indication for an accurate forecast). On the other hand, R-squared, which measures how the model fits a dataset, has a value of approximately 0.8. Therefore, the developed prediction model can be used without reservation, and the expected number of passenger car sales by 2050 can be calculated (82.78 million cars).

Table 2. Passenger car sales prediction model parameters and statistics.

Model	**Model Fit Statistics**		
	R-Squared	**MAE**	**MAPE**
Holt's Model	0.798	2.347	4.081
Prediction Model Parameters			
Parameters	Estimate	SE	t
Alpha (Level)	1.0	0.264	3.783
Beta (Trend)	0.001	0.154	0.004

In order to determine the total annual traveling distance for passenger cars that are expected to be sold in 2050, the average passenger cars daily driving distance has been estimated by using the average values (36.3 km) for the US, Germany (Europe), and China, which are 42 km [22], 32.9 km [20], and 33.9 km [23] (G2), respectively, since these regions have the highest sales of electric vehicles around the world [20]. Using the estimated average daily driving distance and the predicted number of sales in 2050, the total daily traveling distance for these vehicles was calculated (3004.91 million km).

To determine the BEV emission factor (kg CO_2-eq/km) in 2021, the average power consumption of BEVs (kWh/km) and the average emission factor of electricity generation (kg CO_2-eq/kWh) are required. The average power consumption of BEVs was estimated (0.162 kWh/km) using the average value for the top sales models, which are Tesla Model Y (0.164 kWh/km [24]), Tesla Model 3 (0.139 kWh/km [24]), and BYD Atto 3 (0.183 kWh/km [24]) [25]. On the other hand, the electricity generation emission factor was estimated (0.436) by using the average value for the top sales countries, which are China (0.557 kg CO_2-eq/kWh [26]), Germany (0.378 kg CO_2-eq/kWh [26]), and the US (0.373 kg CO_2-eq/kWh [26]).

In order to determine the future (2050) expected BEV emission factor, the future increase in power efficiency of BEVs due to the continuous technology improvement by car manufacturers has been estimated to be 20% every 20 years for new technology vehicles based on several studies in different regions around the world [6,27,28]. Moreover, the future increase in the share of renewable energy in global electricity generation has been considered. It has been approximately 28% in 2021 and it is expected to reach 85% by 2050 [29], as shown in Table 3.

Table 3. Estimated average fuel and electricity consumption rate for global passenger cars and hydrogen and electricity global production emission factors.

Type of Vehicle	Estimated Average Fuel and Electricity Consumption Rate		Estimated Electricity and Hydrogen Production Emission Factors	
	2021	2050	2021	2050
Electric Vehicles	0.162 kWh/km	0.068 kWh/km	0.436 kg Co_2-eq/kWh	0.187 kg Co_2-eq/kWh
Hydrogen Fuel Cell Vehicles (FCEVs)	0.876 kg/100 km	0.374 kg/100 km	12.5 kg CO_2-eq/km	1 kg CO_2-eq/km

Likewise, to determine the HFCBEV emission factor (kg of CO_2-eq/km) in 2021, as shown in Table 4, the average fuel consumption of HFCBEVs (kg/100 km) and average emission factor of hydrogen production (kg CO_2-eq/kg) are required. The average fuel consumption of HFCBEVs was estimated (0.876 kg/100 km) using the average value for tested vehicles in different regions [5,6]. On the other hand, an average hydrogen production emission factor of 12500 gm CO_2-eq/kg was used [5,30].

Table 4. Estimated average global emission factors for passenger cars (EVs and FCEVs) in 2021 and 2050.

Type of Vehicle	Estimated Global Emission Factors (kg of CO_2-eq/km)	
	2021	2050
Electric Vehicles	0.071	0.013
Hydrogen Fuel Cell Vehicles (FCEVs)	0.110	0.004

In order to determine the future (2050) expected HFCBEV emission factors, the future increase in fuel efficiency of HFCBEVs due to continuous technology improvement by car manufacturers has been estimated to be 20% every 20 years for new technology vehicles based on several studies in different regions around the world [6,27,28]. Moreover, the expected use of more eco-friendly hydrogen production methods in the future is considered, which is expected to lead to a production emission factor of 1000 g CO_2-eq/kg in 2050 [30], as shown in Table 4.

Based on the estimated emission factors for BEVs and HFCBEVs and the total daily traveling distance for passenger cars that are expected to be sold in 2050, the expected total annual GHG emissions produced by these vehicles were determined by considering BEV sales in the first scenario and HFCBEV penetration (replacement) in the second scenario, as shown in Table 5.

Table 5. Estimated daily and annual GHG emissions produced by expected sold passenger cars around the world in 2050.

Type of Vehicle	Estimated Global Average Daily Driving Distance (km)	Expected Global Passenger Car Sales in 2050 (Million)	Daily GHG Emissions (Million Tons of CO_2-eq)	Annual GHG Emissions (Million Tons of CO_2-eq)
Electric Vehicles	36.3	82.78	39.064	14,258.36
Hydrogen Fuel Cell Vehicles (FCEVs)			12.020	4387.30

Overall, the results showed that the estimated global emission factors in 2021 were 0.071 and 0.110 kg CO_2-eq per km of travel for BEVs and HFCBEVs, respectively. In other words, HFCBEVs could produce more GHG emissions than BEVs by 54.9% per kilometer of travel. On the other hand, in 2050, the estimated global emission factors were 0.013 and

0.004 kg CO_2-eq per km of travel for BEVs and HFCBEVs, respectively. In other words, BEVs could produce more GHG emissions than HFCBEVs by 225% per kilometer of travel.

The expected number of passenger cars to be sold globally by 2050 could produce approximately 14,258.36 million tons of CO_2-eq annually in the case of BEVs. The expected total annual amount of emissions is approximately 4387.30 million tons of CO_2-eq in the case of HFCBEVs. More specifically, the transformation of passenger cars into HFCBEVs by 2050 (global passenger car sales) could lead to a reduction in emissions by 9871.06 million tons of CO_2-eq. In other words, this reduction is equal to approximately 34.5% of the global energy-related GHG emissions in 2022, which is approximately 41.3 Gt CO_2-eq [31].

5. Conclusions

In this study, the impacts of HFCBEV future sales on global GHG emissions compared to other technologies such as BEVs were determined based on the predicted sales for 2050 (the result of the prediction model), the estimated daily traveling distance, the estimated future average global electricity emission factors, the future average BEV emission factors, the future global hydrogen production emission factors, and the future average HFCBEV emission factors. The expected annual GHG emissions produced by passenger cars that are expected to be sold in 2050 were determined by considering BEV sales in the first scenario and FCEV replacements in the second scenario. It is worth mentioning that one of the main limitations of this study is the drop in global passenger car sales during the pandemic, which could affect the prediction model results; however, this study has focused on the comparison between BEVs and HFCBEVs, which means that any prediction error in the number of passenger car sales will affect the impact assessment of both BEVs and HFCBEVs equally; therefore, the environmental impacts as a percentage will not be affected. Moreover, estimating hydrogen production emission factors in 2050 is considered one of the constraints in this study, due to the unexpected factors that can affect this industry in the long term. After analyzing the results, the following conclusions were obtained:

- Global passenger car sales are expected to significantly increase in the future, with up to 44% in 2050 compared to 2022, owing to the increasing demand for passenger transport and the increase in fuel efficiency by using new vehicle technologies, which leads to a continuous reduction in operation costs.
- The environmental benefits of HFCBEVs are expected to increase over time compared with BEVs because of the eco-friendly methods that are expected to be used in hydrogen production in the future. For instance, in 2021, HFCBEVs could produce more GHG emissions than BEVs by 54.9% per km of travel, whereas in 2050, BEVs could produce more GHG emissions than FCEVs by 225% per km of travel.
- In 2050, the expected number of passenger cars to be sold could produce approximately 14,258.36 million tons of CO_2-eq annually in the case of BEVs. On the other hand, the expected total annual amount of emissions is approximately 4387.30 million tons of CO_2-eq in the case of HFCBEVs. In other words, HFCBEV sales in 2050 could achieve a drastic decrease in GHG emissions, which is equal to approximately 34.5% of the energy-related global GHG emissions in 2022.
- In addition to the expected environmental benefits of HFCBEVs compared to BEVs, HFCBEVs could address the main drawbacks of BEVs (long refueling time and limited range) because the refueling time of HFCBEVs does not take more than a few minutes, and the range of vehicles is expected to increase significantly.
- Heavy vehicles such as buses and trucks will dominate hydrogen use in vehicles, because they beat batteries in relation to weight, range and cost. Moreover, using this technology in taxis could lead to more benefits than passenger cars due to the longer distance traveled by taxis.
- It is recommended to include heavy vehicles powered by fuel cells in future studies, since only passenger cars were included in this study because of the absence of relevant information.

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