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RESEARCH

Comparison of energy consumption and global warming potential of electric and hydrogen-fueled vehicles across different product size

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Abstract The electrification of public transport is important for a sustainable future and directly serves the 11th goal of the SDGs, which is Sustainable Cities and Communities. Nowadays, transportation emissions are increasing day by day. Within the scope of this study, the energy consumption and global warming potential (GWP) analyses of three different types of vehicles (12-m electric, 12-m FCEV fuel cell, and 18-m electric) during their production and usage phases were compared, aiming to guide a sustainable future. For the usage phase of the product, life tests and literature studies were used, regression modelling was utilized for the manufacturing stages, and the SimaPro Ecoinvent module was used for GWP. Within the scope of the study, three different EV and HFC commercial vehicles coming out of the same production line were compared in terms of energy consumption, and while the 12-m electric vehicle had the lowest energy consumption (1.625 kWh/km), the 18-m electric vehicle had the highest energy consumption (2.250 kWh/km). Comparing the GWP potentials of the vehicles, 12-m EV ($5.97*10^{-4}$ GWP), 12-m FCEV ($1.31*10^{-3}$ GWP), and 18-m EV ($2.57*10^{-3}$ GWP) were calculated for the manufacturing stage. In the use phase, the GWPs of the three vehicles were calculated to be approximately the same. Future studies can contribute to the carbon-neutral roadmaps of countries by calculating the carbon footprint and environmental impact analysis across all processes from cradle to grave.

Highlights

- EV and FCEV vehicles contribute directly to the SDG targets for a sustainable future.
- 12-m EV and 12-m FCEV are more advantageous in terms of energy consumption and GWP in the manufacturing phase.
- FCEVs may be more advantageous than EV technology after hydrogen purification and widespread use.

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Introduction

The three main issues with energy usage are growing costs, the depletion of fossil fuel resources, and environmental issues (Kalair et al., 2021). One of the most important strategies to get beyond these obstacles is to use renewable and alternative energy sources (Bayati, et al., 2020). Another strategy to increase the system's efficiency is to share power among several components and use many energy sources simultaneously (Bayati et al., 2022). One of the largest sectors that uses a lot of energy is the transportation sector (Umar et al., 2021). Internationally, a variety of industrial sectors have been taking action to reduce CO_2 emissions. On the other hand, the transportation sector focused on further electrifying what are referred to as new energy vehicles. This is particularly true for land transportation, which is a major source of pollution (Smith et al., 2016). Governments throughout the globe are paying more attention to the transportation industry because of its substantial influence on greenhouse gas emissions and environmental pollution (Zhang, et al. 2019; Zou, et al. 2016). Electric cars, or EVs, have become more popular as sustainable and environmentally beneficial modes of transportation (Mohammadi & Saif, 2023). The adoption of EVs holds significant potential to address the energy and environmental challenges posed by the existing transportation system. First, electricity can address forthcoming transportation requirements (Wu et al., 2015). However, some disadvantages of electric vehicles, such as long charging times and limited range, affect their alternatives to internal combustion engine vehicles; fuel cell electric vehicles may offer a more favorable perception to the driver compared to battery electric automobiles (Selmi et al., 2022, Savran et al., 2024). Automakers are offering alternatives to fossil fuels for vehicle propulsion; these include battery systems, ultracapacitors, and fuel cells. Electric vehicles (EVs) and fuel cell electric vehicles (FCEVs) represent the most effective solutions to reduce greenhouse gas (GHG) emissions and other pollutants. However, although they can significantly reduce emissions, they do not eliminate them (Xun et al., 2018). Fuel cell electric vehicles can present a more optimistic picture to the driver than battery electric vehicles. Optimizing energy use is crucial to improving global energy efficiency. Reducing energy use in transportation is among the most repeated goals in energy consumption optimization problems (Ghorbani et al., 2023). In 2011, the International Standards Organization (ISO) published ISO 50001, which delineates the characteristics and application of the energy management system (Güllü & Yakışık (2017). ISO 50001 facilitates the ongoing enhancement of consumption efficiency, without delineating a specific assessment criterion for energy (Savran et al., 2022). Accurate estimation of EV energy consumption is quite complex as it depends on several variables such as road topology, traffic conditions, driving style, and ambient temperature (De Cauwer et al., (2015). In addition, battery state of charge (SOC) and energy efficiency of regenerative breaking are other important parameters (Liu et al., 2016). The majority of studies in the literature on electric vehicles have focused on estimating the factors and impacts affecting energy consumption (Ghorbani et al., 2023, De Cauwer et al., 2015, Liu et al.. 2016, Li et al., 2016, Qi et al., 2018, Qi et al., 2018, Zhang et al., 2020, Fetene et al., 2017, Teixeira & Sodré (2018). The focus of this study, unlike others, is to reduce electricity consumption in the product and production stages of electric and fuel cell electric vehicles with validated models and to conduct environmental impact analyses throughout the entire life cycle of the product. To increase power density in vehicles and meet load power demand, energy management systems need to be integrated. The strategy of fuel cell electric vehicles in this regard is based on finite state machine management strategies (Wang et al., (2019), gray wolf optimizer (Djerioui et al., (2019), model predictive control (Li et al., 2019), fuzzy logic control (Ahmadi et al., 2018; Harrabi et al., 2018), genetic algorithms (García et al., 2013; Geng et al., 2019), hierarchical estimation (Liu et al., 2019; Fu et al., 2019), and other developed energy management system control techniques (Sorlei et al., 2021).

Energy consumption occurs in raw material production, bus assembly lines, real-world driving, and recycling processes. Energy consumption is an important part of sustainable mobility (Yavaş et al., 2022; Habib & Butler 2022), especially in real-world driving conditions. If an electric vehicle with low energy consumption in raw material and production stages consumes high energy during use, this negatively affects the efficiency of the entire mobility process. There are many factors such as power management strategies, air conditioning systems, regenerative braking, and driver behavior (Savran et al., 2024a, b, c; Savran & Karpat, 2024) to increase energy efficiency. In the approaches created to achieve energy consumption reduction, optimization studies are mostly made between consumption and vehicle performance (Savran et al., 2024a, b, c). Improvements made specifically in driver behavior will satisfy both the user and future generations thanks to the reduced environmental impact. In addition, the length, mass, architecture, and chosen components of a vehicle also play an important role in determining energy consumption and environmental emissions (Mehranfar et al., 2024). Despite similar length and mass, vehicles with different architectures may differ in their energy consumption. In addition, the consumption of a vehicle with the same architecture but different lengths may also vary. For this reason, low-floor electric buses with different architectures and lengths are considered in this study.

This study aims to examine the energy consumption values of electric and fuel cell buses with different architectures and capacities during the raw material stage, production, and real-world driving conditions and to determine their carbon emissions. The comprehensive analysis of energy consumption and carbon emissions throughout the vehicle life cycle of electric vehicles, which are pioneers of sustainable mobility, aims to develop environmentally conscious driving support systems and train driver candidates. In addition, recommendations for reducing energy consumption and carbon emissions were shared with the reader according to the output obtained because of the comprehensive analysis, and the environmental impact of electric vehicles from cradle to grave was revealed.

Materials and methods

Energy consumption in real-world driving

Within the scope of the study, the energy values of three different types of electric buses during the manufacturing stage and the real-world driving phase will be compared with each other (see Figure 1).

The buses assessed in this study have bus architectures of 12–18-m battery electric and 12-m fuel cell electric. Buses in lengths of 12 m and 18 m have batteries for electric energy storage, while a 12-m FCEV has a hydrogen tank and a battery. Since 18 m is an articulated bus, the only outward difference includes a case connector. General visualizations can be seen in Figure 2.

Energy efficiency calculations

The study calculated energy consumption using four different methods: compressed air equipment, pump/motor group equipment, heating/cooling systems, and lighting systems. The PowerStudio SCADA® system measures the equipment's energy consumption at intervals ranging from 1 min to 1 year (15 minutes, hours, days, months, and years). SCADA calibrations are performed and monitored annually by a third-party ISO 17025 accredited by the manufacturer.

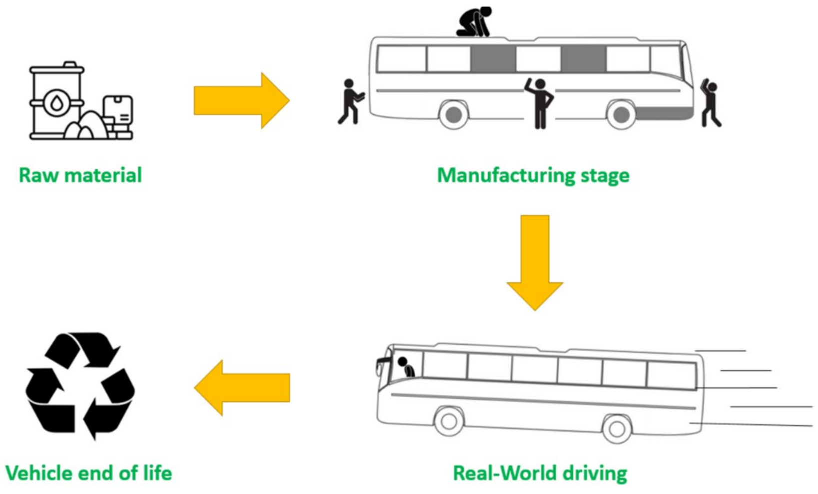

Fig. 1 Energy consumed and carbon released stages of an electric vehicle

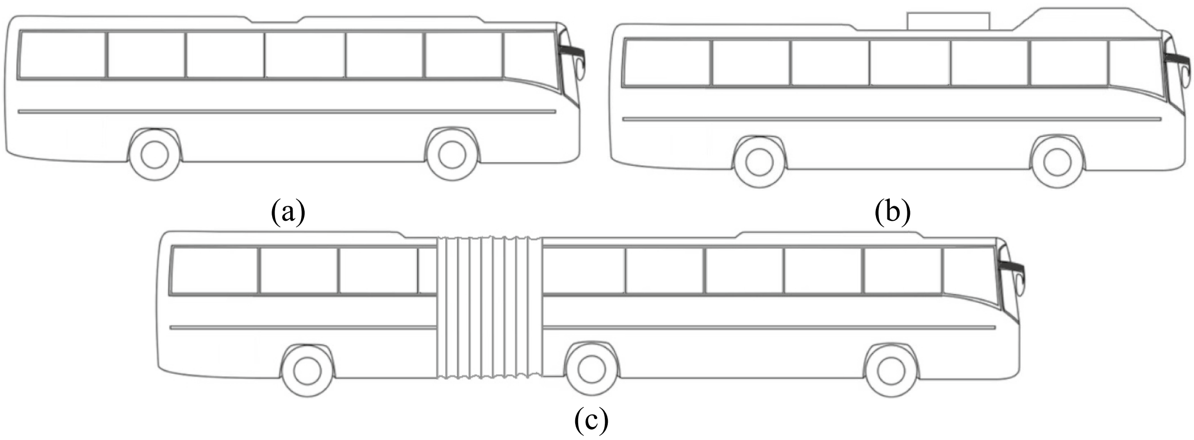

Fig. 2 Bus type illustrations. **a** 12-m battery electric bus. **b** 12-m FCEV. **c** 18-m battery electric bus

Compressed air equipment will be obtained from tag power and SCADA data. Also, in addition to SCADA, measurement results from the energy audit feasibility study were also used to calculate specific energy consumption (SEC). Specific energy consumption:

$$SEC = Total\,energy\,consumption(kWh) / Total\,vehicle\,production\,(prod.) \quad (1)$$

Table 1 displays the measurement equipment and their specifications used in the study. All measurements were made to the same standards, and the measurements and calculations during the manufacturing stage are detailed in Table 1.

The vehicles compared in the study produced in the same line. Therefore, for commercial confidentiality, the vehicles are compared with the energy they produced in same line production line, since they produced in same line. Energy consumption rates:

$$Energy\,Consumption\,Rate\,(\%) = [Energy\,Consumption\,(kWh) / Line\,Consumtion\,(kWh) \quad (2)$$

Table 1 Measurement equipment used in the study

Brand	Model	Serial No.	Device type	Date of calibration
Chauvin Arnoux	CA8331B	182155 WFH	Energy analyzer	19/07/2023
Chauvin Arnoux	F407	101127UAC	Energy analyzer	27/09/2023
Dimens	TUF200H	82106970H	Ultrasonic Liquid flow meter	23/12/2023
Testo	405i	48918226	Bluetooth wire anemometer	30/09/2023
Testo	605i	49344759	Bluetooth humidity meter	30/09/2023
Testo	510i	46272783		03/10/2023
Testo	320	30238998	Flue gas analyzer	24/03/2023
Testo	882	02016522	Thermal camera	23/03/2023
Lutron	LX- 1108	Q290384	Luxury meter	17/03/2023
Testo	410i	46477068	Propeller-type anemometer	03/02/2023
Vpinstrument	VpsR200p400	515344	Immersion-type compressed air flow meter	10/08/2023
Leakshooter	LKS1000-V2+	T3563	Ultrasonic leak meter	Out of scope

Linear regression analysis

Linear regression analysis is a reliable numerical method to see the energy consumption evaluation and prediction. This method is a modelling type that predicts the desired values by handling the easily detectable variables. Also, it is stated that regression analysis is affected by extreme values and distribution properties (Kilic, 2013). Linear regression analysis is a useful tool to indicate the value correlations and future prediction. Since this study aimed the energy management for electric bus manufacturing, the authors focused on energy consumption per years (Yavas et all., 2022).

In this study, three different vehicles (12-m EV, 12-m HFC, and 18-m EV) manufactured on the same production line will be analyzed by regression analysis and their energy consumption during the production phase will be compared. The x-axis of the regression analysis will include the number of units produced (monthly), and the y-axis will include the monthly energy consumption without taking into account the loss values.

Global warming potential for production

The first step for the global warming potential is to define a functional unit for the system. Since only the results of the production and product phases are considered in this context, the functional unit is the comparison of the energy required to transport 1 passenger 1 km by 1 vehicle. The calculation of the energy values for the manufacturing stage is described in the "Energy consumption in real-world driving" section, and the energy values for the product phase are obtained using the method described in the "Energy efficiency calculations" section. The SimaPro Ecoinvent module is used to calculate the GWP of these data. This module calculates all results according to the IPCC 2021 GWP 100 V1.02 value, and the carbon emissions due to energy in the manufacturing stage are verified on an annual basis according to the ISO 14064 - 1 standard. In this study, global warming potential is considered as carbon dioxide equivalent emissions (CO_{2equ}).

Results

Energy consumption in real-world driving

To represent the real conditions, energy consumption values were considered in literature. For instance, the 1.625 kWh/km (Topal, 2024; Perugu et al., 2023) was accepted for a 12-m battery electric bus. For 18 m, 2.25 kWh/km was chosen among 2.25 kWh/km (Topal, 2024; Perugu et al., 2023), 1.9–2.5 kWh/km (Jahic et al., 2023), and 0.99–2.42 kWh/km (Jahic et al., 2023). When it comes to a 12-m fuel cell electric bus, a 7.99 kg H_2/100 km value appeared apart from 7 kg H_2/100 km (Caponi et al., 2023), 7.99 kg H_2/100 km (Danielis et al., 2024), and 9 kg H_2/100 km (Kim et al., 2021). Bus technical specifications such as battery capacity, consumption, driving range, and driving results for a million km are given in Table 2.

Fuels have variable usable energy densities, for instance, 9.56 kWh/l (Das et al., 2024), 10.53 kWh/l (Das et al., 2024), and 33.33 kWh/kg (Yue et al., 2021) for gasoline, diesel, and hydrogen, respectively. The nominal fuel cell module efficiency value can be

Table 2 Technical specifications of buses

	12 m	12 m fuel cell	18 m
Energy capacity	320 kWh (UITP, 2022)	29.2 kWh (Wagner & Walther, 2024) 36 kg H_2 (Wagner & Walther, 2024)	450 kWh (Wager et al., 2016)
Consumption	1.625 kWh/km (Topal, 2024; Perugu et al., 2023)	7.99 kgH_2/100 km (266.3 kWh/100 km) (Danielis et al., 2024)	2.25 kWh/km (Topal, 2024; Perugu et al., 2023)
Range	197 km	468 km	200 km
Passenger capacity	90	90	135
Energy consumption (1 million km)	1,625,000 kWh	1,625,000 kWh	2,250,000 kWh
Battery cycle (1 million km)	5,078	2,582	5,000

accepted as about 50% (Naganuma & Sakane, 2023). According to efficiency and hydrogen energy density, a 12-m fuel cell electric bus has a usable energy capacity of 629.1 kWh in total. The fuel cell system accounts for 95.36%, while the battery accounts for 4.64% of the total energy capacity. Therefore, 75,400 kWh of 1,625,000 kWh is used from the battery, and the battery will have 2582 cycles in a million km. In Table 2, the FCEV's 7.99 kgH_2/100 km and 1,625,000 kWh are not directly related. The 12-m FCEV technically has the same infrastructure as the 12-m vehicle, which is a battery electric vehicle, and its energy consumption per km is the same as the 12-m battery electric vehicle. The 7.99 kgH_2/100 km corresponds to the amount of hydrogen that will be consumed, depending on the efficiency value of the fuel cell module, which is the energy that needs to be produced.

Battery cycle life is responsible for electric bus life. Because battery life is affected by several factors, it is hard to estimate the exact life cycle. In a study (Preger et al., 2020), battery cycle limits were stated as between 2500 and 9000 full cycles for LFP, between 250 and 1500 full cycles for NCA, and between 200 and 2500 full cycles for NMC cells. Regarding 9000 full cycles in LFP battery life, a 12-m battery electric bus can be driven for 1,772,351.3 km, a 12-m fuel cell bus can travel 3,485,670 km, and the battery of an 18-m battery electric bus can be used for 1,800,000 km.

Energy efficiency calculations

The production of electric buses consists of three main processes: body, painting, and assembly. Energy is consumed in the body, paint, and assembly facilities. Electric vehicles are an important part of countries' sustainability goals. This importance has ensured that one of the 17 SDG goals is directly integrated with sustainable transportation. For this reason, monitoring and reducing the energy consumption of electric vehicles during the manufacturing stage will also reduce carbon emissions accordingly. Within the scope of this study, the energy consumption rates of a 12-m electric vehicle, a 12-m FCEV, and an 18-m electric vehicle are shown in Figure 3.

When Figure 3 is examined and the results are compared with each other, the least energy consumption per product was found in the 12-m electric vehicle, followed by the 18-m electric vehicle, and the highest energy consumption was identified in the FCEV. The numerical results were obtained as 28%, 30%, and 42%, respectively (Eq. 2). When examining the impact of the product type (electric-hydrogen fuel) on energy consumption, it is observed that the electric vehicle consumes 15.4% less energy per product compared to the FCEV, while the difference in vehicle length (12 m electric–18 m electric) has a 3.2% impact on energy consumption during the manufacturing stage.

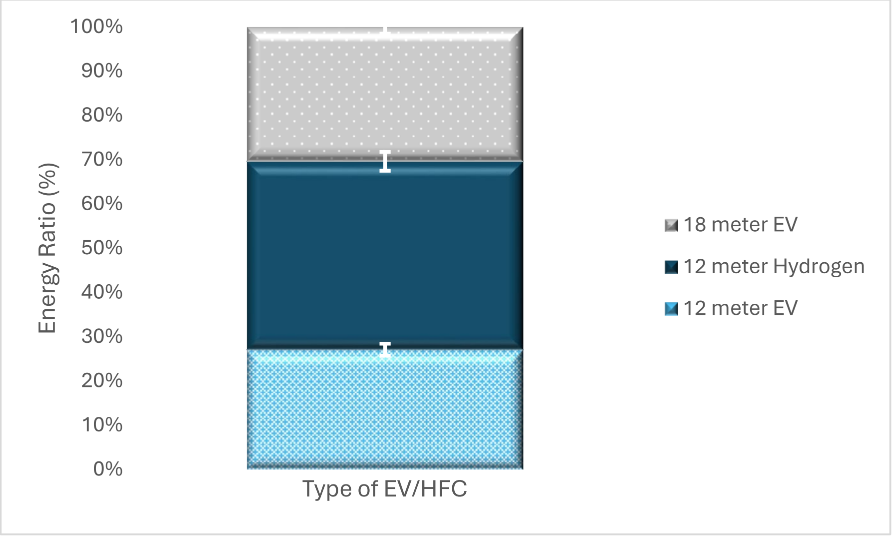

Fig. 3 Comparison of energy consumption rates of 12-m EV, 12-m HFC, and 18-m EV vehicles on the same production line

Additionally, within the scope of the study, the regression curves of three different vehicles were examined, and the impact of product-dependent and product-independent energy during the manufacturing stage was compared. The results of the regression analysis are presented in Figure 4.

Looking at the results of the regression analysis, it has been observed that the energy values in the production of electric vehicles and FCEV are more independent of vehicle production. Looking at the statistical values, it has been observed that they are affected by energy consumption, with the degree of impact being highest for the following vehicle types: 18-m EV, 12-m FCEV, and 12-m EV. R^2 values are expected to be greater than 0.7, but the low production of heavy commercial vehicles and the long waiting times on the production lines mean that there is a lot of energy lost on these vehicles. We predict that as compliance with sustainability requirements increases and the demand for vehicles rises accordingly, the losses will decrease and the R^2 value will increase.

In Figure 4, as production increases, consumption also increases as expected in all data sets. The consumption of 12-m HFC vehicles is much more sensitive to the increase in production, i.e., a one unit increase in production increased the consumption of 12-m HFC vehicles much more than other vehicles. For 12-m EV vehicles, it is concluded that consumption increases more steadily as production increases.

Global warming potential

The global warming potential shows the degrees to which the material affects global warming during the production and product stages. Within the scope of this study, the GWP rates of 12-m electric, 12-m FCEV, and 18-m electric vehicles have been compared with each other (Figure 5).

When examining Figure 5 and evaluating the GWP-fossil impact, it is observed that during the manufacturing stage, the 18-m electric vehicle has a greater impact (approximately 60%) compared to other product groups. Throughout their entire lifespan, these vehicles have almost the same impact. When examining the GWP-biogenic effect, it is observed that the 12-m FCEV has a greater impact (approximately 65%) during the manufacturing stage

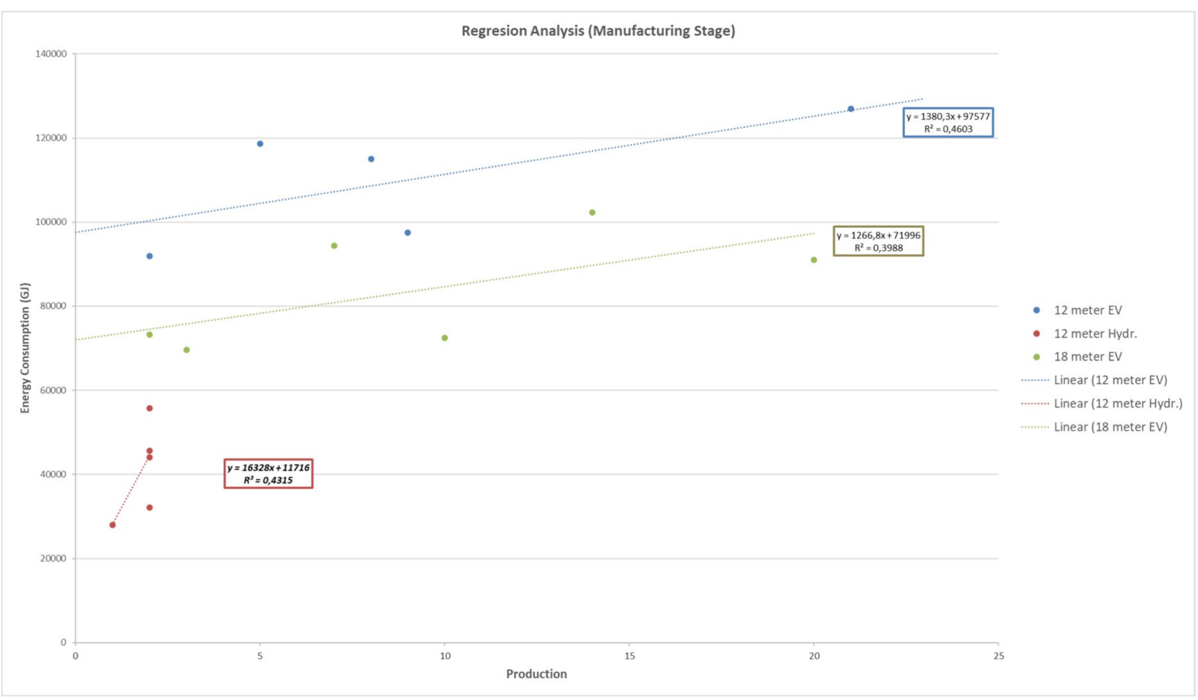

Fig. 4 Model results explaining energy consumption and the relationship in the manufacturing stage

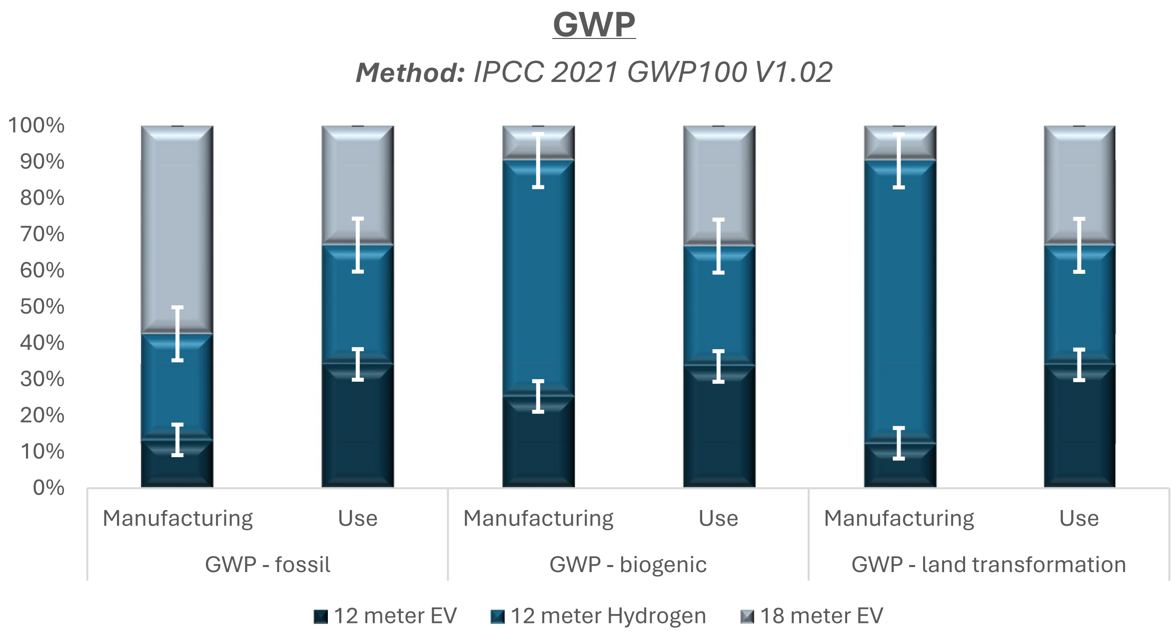

Fig. 5 GWP comparison of 12-m EV, 12-m FCEV and 18-m EV

compared to the others. During the usage phase, these vehicles have an equal impact on each other. When looking at the GWP land transformation impact, it has been determined that the FCEV alone has a 75% impact. The GWP impacts of the products are detailed in Figure 6 as Sankey diagram.

When the Sankey diagram is examined, it is seen that the GWP-land transformation effects are the least in all vehicle types, and the highest effect is in the GWP-fossil category. The effect of biogenic and land transformation is negligible compared to the fossil effect as shown in Figure 6. The energy consumption and GWP values of three different vehicles during production and use phases are summarized in Table 3.

Table 3 shows us the ratios of the GWP potentials of these three different vehicle groups among themselves and the ratios of each other in the production and use phase. According to these results, when comparing three different vehicles, we can see that the 12-m electric vehicle has the lowest impact. Although the hydrogen-fueled vehicle achieves better results than the 18-m vehicle in terms of GWP values, its energy consumption in the manufacturing stage is higher than that of the 18-m vehicle.

Discussion

Within the scope of the study, three different types of electric vehicles have been compared with each other in terms of energy consumption during the production and product usage phases. The energy consumption of electric vehicles has become increasingly important in today's world, especially in terms of meeting sustainability requirements such as the EU Green Deal. Especially in line with the EU's 2050 carbon neutrality goals, they aim to see 13 million vehicles on the roads by 2030. In this context, not only the energy and carbon consumption of electric vehicles on the roads but also the energy consumption during the manufacturing stage are issues that need to be monitored to achieve this goal. The study has made an innovative contribution to literature in this regard as well.

Umar et al. compared internal combustion engines with biomass fuels in terms of air quality in a study, conducted in 2021 and measured the air quality in the USA. As a result of the study, they observed that fossil fuels and biomass fuels have a negative impact on air quality (Umar et al., 2021).

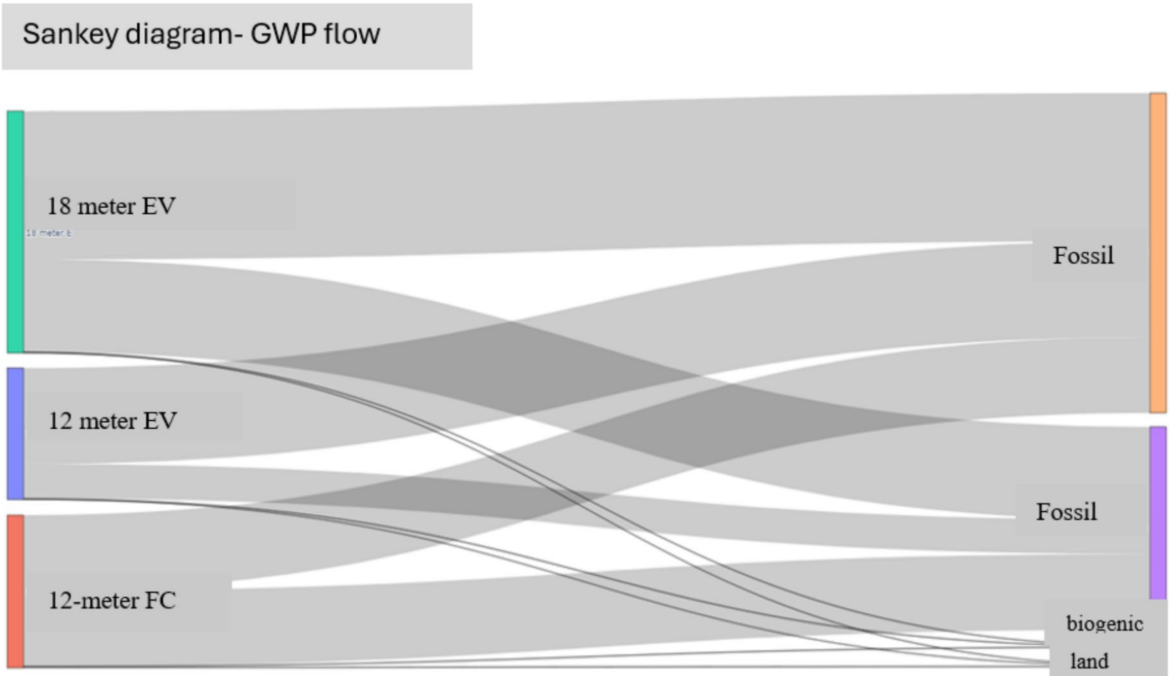

Fig. 6 IPCC 2021 impact GWP values of the products

Table 3 Comparison of energy consumption and GWP results in the production and use phases

	GWP - fossil		Energy Consumption		Total	
	Production	Use	Production	Use	GWP	Energy
12-meter EV	10%	32%	23,6%	29,5%	21%	26%
12-meter FCEV	31%	34%	44,5%	29,5%	32,5%	31%
18-meter EV	59%	34%	31,9%	41%	46,5%	43%

Similarly, in a comparable study conducted on mountain roads in Albania, the energy consumption of internal combustion engines and electric vehicle batteries was compared, and the energy consumption of the Golf Diesel and RAV 4 Diesel was measured as 193.89 Wh/km and 284.2 Wh/km, respectively. Additionally, the energy consumptions of the electric versions of the same vehicle were measured as 75.91 Wh/km and 93.98 Wh/km, respectively (Travesset-Baro et al., 2015). As a result of this study, the consumption values of the electric vehicle were analyzed as 1.62 kWh/km and 2.25 kWh/km for the 12-m and 18-m vehicles, respectively.

In a study conducted by Saikong and Kulworawanichpong in 2017, they compared the energy consumption of electric vehicles in the Pb, Li-I, and HESS battery groups. In this context, they found the energy consumption of the batteries to be 15.84 kWh, 6.41 kWh, and 6.36 kWh, respectively (Saikong & Kulworawanichpong, 2017). In another study conducted by Albatayneh et al. in 2020, energy consumption at all stages was compared for internal combustion and electric vehicles, and ways to make them more efficient were discussed. Especially as the consumption rate of renewable energy increases, it has been observed that electric vehicles become 40–70% more energy efficient. When looking at the energy efficiency of vehicles, internal combustion engines achieve 12–25% efficiency for GWP, while electric vehicles can achieve 42–72% efficiency for GWP, especially when using renewable energy (Albatayneh et al., 2020). Since thermal conversion losses are relatively lower in the use of renewable resources compared to oil or coal, there is potential for increased efficiency. In our study, these results were found to be 1.62 kWh/km for the 12-m electric vehicle and 2.25 kWh/km for the 18-m electric vehicle. For the 12-m FCEV, the energy consumption value is 7.99 kgH_2/100 km.

Savran and others conducted a study in 2024 on the hydrogen consumption and battery cycle reduction of a fuel cell vehicle by an optimization algorithm, and according to the study results, they observed that the total hydrogen consumption of the fuel cell electric vehicle decreased by 57.8% under hybrid driving conditions, by 23.3% with two battery packs under constant speed driving conditions, and by 36.27% with three battery packs (Savran & Karpat, 2024). In their study, Naganuma and Sakane evaluated FCEV in terms of fuel consumption under real road conditions. The average fuel consumption of the hydrogen-powered series hybrid vehicle exceeded the average fuel consumption of the gasoline-powered series hybrid vehicle under all conditions, and they found that in urban and winding conditions with frequent acceleration and deceleration, the fuel cell vehicle performed better. In terms of CO_2 emissions, when it comes to life cycle assessment, fuel cells and electric vehicles have emitted more CO_2 throughout the production process. When it comes to fuel production, the CO_2 emissions from hydrogen and electric vehicles depend on the energy source. However, in the future, this issue can be resolved by using non-carbon energy sources for fuel production. Therefore, hydrogen-powered series hybrid vehicles show high potential as environmentally friendly alternative fuel vehicles (Naganuma & Sakane, 2023). Habib, in a study conducted in 2023, using machine learning for the energy management system of FCEV, calculated the energy efficiency of Li-I batteries to be 20–66%, while FCEV was calculated to have an efficiency of 65–95% (Habib, 2023). Selmi et al. examined the performance of FCEV in 2022 for 7 different models of 13 different passenger cars and determined that hydrogen fuels consumed 89–116 km/kg of hydrogen with a power of 10 kW and a range of 400–756 km (Selmi et al., 2022). In our study, the energy consumption performance of a 12-m FCEV was calculated under real road conditions compared with a 12-m electric bus and an 18-m electric bus. In the results obtained, it was observed that the 12-m FCEV reached a driving range of 468 km (with the consumption as 7.99 kgH_2/100 km). At the same time, it has been calculated that the total energy consumption is the same as that of a 12-m electric vehicle and 26% less than that of an 18-m electric vehicle (Danielis et al., 2024).

Increasing sustainability demands and countries' pressures for carbon neutrality necessitate the use of new technologies in terms of sustainability. Especially electric public transportation vehicles and the FCEV versions that have started to be used in recent years, it is important to know their contribution to sustainability processes. In this study we conducted, the energy consumption during both the production and transportation phases of three different sustainable products—12-m electric, 12-m FCEV, and 18-m electric—was compared, and their impact on GWP was calculated. Parikh et al. conducted a similar study in 2023, analyzing the efficiencies, performances, advantages, and disadvantages of different fuel cells and batteries. In a study, it is observed that due to challenges such as extraction and purification of hydrogen throughout its life cycle, electric vehicle batteries are still more advantageous (Parikh et al., 2023). Desreveaux et al. (2023) examined the impact of energy consumption in vehicles on climate change and proved that by including the secondary life of batteries in the process, they are 43% (45 g CO_2eq/km) less in terms of GWP (Desreveaux et al., 2023). Kamath et al., on the other hand, analyzed electric vehicle batteries in the USA in 2023 using the system dynamics model, focusing on cost, carbon, and recycling needs. In their findings, they discovered that recycling or reusing the battery would provide 2–17% efficiency in terms of LCA. Nalbur and Yavas (2024) examined the emissions of electric buses, particularly those caused by supply and transportation, using a system dynamic model and found that they could have a positive impact on the vehicle's GWP by 22–90% (Nalbur & Yavas, 2024). Our study focused on the GWP analysis of 12-m and 18-m electric vehicles and 12-m FCEVs, and according to the GWP results, the lowest GWP was determined to be for the 12-m electric vehicle, followed by the 18-m electric vehicle, and the highest for the FCEV. Additionally, according to the analysis results, the GWP results for all three vehicles were reported as < 30 g CO_2eq/km. These results, especially for buses classified as heavy commercial vehicles, demonstrate their positive impact on a sustainable future while also indicating that hydrogen technologies can become a highly sustainable product by minimizing risks such as purification and transportation.

Conclusion

Within the scope of the study, the energy consumption of 12-m electric, 18-m electric, and 12-m FCEVs during both the production and usage phases was compared, and GWP analyses were evaluated for a sustainable future. The results show that during the usage phase, the vehicles have highly efficient consumption, respectively: 12-m electric, 12-m FCEV, and 18-m electric. Additionally, the energy consumptions during the manufacturing stage of these three products were found to be 12-m electric, 18-m electric, and 12-m FCEV, respectively. The results were also evaluated with a total GWP analysis, and the contributions of the usage phase to the GWP are almost the same for all three vehicles. However, it is observed that FCEV has higher energy consumption during the production stages.

Future studies should focus not only on the impact of these three vehicles during the production and usage phases but also on all processes from cradle to grave, to develop a roadmap for more carbon-neutral vehicles. Additionally, the products' entire environmental impacts, not just their GWP, should be examined cradle-to-grave, and it is of utmost importance for manufacturers to develop their roadmaps based on these results.

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Declarations

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