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Life Cycle Energy Consumption and Air Emissions Comparison of Alternative and Conventional Bus Fleets in Vietnam

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Abstract: The study (a) assesses the life cycle energy consumption and air emissions impacts of battery electric buses (e-buses) and conventional buses operated in Vietnam, and (b) compares them with those of hydrogen buses. The results indicate that e-buses and hydrogen buses are preferred options compared to conventional buses in terms of energy consumption, GHG emissions and other air quality impacts over their whole life cycle. Life cycle energy consumption of diesel buses is triple that of e-buses, and is significantly higher than that of hydrogen buses. Replacing conventional buses with e-buses can reduce energy consumption by 50%. For GHG emissions and air quality impacts, the adoption of electric and hydrogen mobility in replacement of conventional buses will reduce GHG emissions by 39%, and other impacts related to air quality by 13% to 90%.

Keywords: e-bus; hydrogen bus; energy consumption; GHG emissions; air quality; LCA

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1. Introduction

Transportation is a significant source of greenhouse gas (GHG) emissions and air pollutants in urban areas. It contributes to about one-third of global GHG emissions [1], 27% of GHG emissions in European (EU) countries [2,3]. Furthermore, 56% of NOx, 13% of SOx, 20% of $PM_{2.5}$, and 14% of PM_{10} in EU countries originate from transportation activities [4]. The EU's Green Deal aims at cutting GHG emissions by at least 55% by 2030 compared to the emission level of 1990, and aims at carbon neutrality by 2050 [5]. In order to achieve the targets of GHG emissions and improving air quality in urban areas, the transportation sector needs to decarbonize and improve its efficiency. One of the options is electrification of the transportation systems [6]. The electrified transportation systems have no end-of-tail emissions. Therefore, when comparing different options of transportation, either conventional or electrified ones, the life cycle thinking should be applied to avoid transferring the impacts of one stage to others. Over their life cycle, many studies indicate that electrified transportation systems have lower GHG emissions [7–16]. In Italy, the life cycle environmental impacts of hydrogen fuel cell vehicles (HFCVs) and battery electric vehicles (BEVs) are compared, and it is found that with the Italian electricity mix, the GHG emissions of BEVs are at 35.65 $kgCO_2eq$ for an average day route of 20 km, much lower than those of HFCVs, at 96.38 $kgCO_2eq$ [7]. More recently, another study on transportation activities in Milan and Turin, Italy, estimates that the adoption of electric vehicles (EVs) in replacement of internal combustion engine vehicles (ICEVs) helps to reduce 40% of the climate change impacts [10]. In other countries, ICEVs are found to emit more GHGs than EVs, for example in Poland and the Czech Republic [8], 70% more GHGs in the United States of America (USA) [9], 18%–23% in China [17], and 24% in Hong Kong [18]. The emission reduction benefits are various among different types of EVs. For example, BEVs and plugin hybrid EVs (PHEVs) emissions are found to be 17–23% lower than those of ICEVs in China [16]. Another study in China indicates that HFCVs fueled by green hydrogen such as hydropower-based hydrogen have much lower GHG emissions than BEVs. However, if HFCVs are fueled by blue hydrogen, such as natural gas-based hydrogen, their GHG emissions are higher than BEVs charged by grid electricity, and similar to those of ICEVs [12].

The life cycle GHG emissions of EVs considerably depend on the electricity used to charge the cars in the case of BEVs, or the electricity and technologies used for producing hydrogen in the case of HFCVs. In all the studies carried out with future electricity scenarios in which a higher share of renewable energy sources (RES) are integrated into the grid, the life cycle GHG emissions of EVs are significantly reduced. For example, the life cycle GHG emissions of HFCVs in Germany are currently at 150 gCO_2eq per km. In the future, electricity scenarios with more RES and increased fuel tank, fuel cell and battery efficiency, the life cycle GHG emissions of HFCVs will be reduced by nearly 40%, to 90 gCO_2eq per km [19]. Moreover, in China, thanks to the reduction in emission intensity of the electricity grid, the life cycle GHG emissions of EVs would decrease by 16.8% in 2020, compared to those of 2015 [11], and by 2030 EVs are forecasted to save 49.64 million tonnes to 62.16 million tonnes of GHGs, depending on different scenarios of technological improvement in battery efficiency and fuel/electricity consumption [20].

The important role of electricity was indicated by the difference of GHG emissions of EVs in various deployment contexts. The life cycle GHG emissions of EVs in Poland are higher than those of the Czech Republic, as the Polish electricity mix has higher emission intensity than that of the Czech Republic [8]. Furthermore, this is clearly shown in the considerable difference in GHG emissions of BEVs in the Organization for Economic Cooperation and Development (OECD) and non-OECD countries. Specifically, the life cycle GHG emissions of BEVs in India could be 2.5 times larger than those of North America due to the higher emission intensity of the Indian electricity grid mix [21]. In another case, BEVs in Vermont, Oregon and New Jersey emit less GHGs than those in other US states thanks to the large shares of hydro and nuclear power in these three states' electricity grids [22].

In some cases, a fossil fuel-intensive electricity grid makes EVs no longer a clean and sustainable choice. For example, in Lithuania, the national electricity mix is oil intensive. As a result, EVs charged with the national electricity mix emit 26–47% higher GHGs than ICEVs [23]. This situation also occurs in Korea and Australia in which the use of BEVs leads to higher life cycle GHG emissions compared to diesel buses due to the coal-intensive electricity grids [24,25]. In the Chinese context, BEVs are not recommended until the grid's emission intensity becomes lower than 320 gCO_2eq/kWh, which was forecasted to be in the next 20 or 30 years [26]. Table 1 summarizes a comparison of the GHGs of BEVs, HFCVs and ICEVs with different electricity sources in the existing literature.

Table 1. Life cycle GHG emissions of EVs, HFCVs and ICEVs in existing literatures.

Author	Year	Product Systems	Country/Region	Electricity	GHG Emissions	Functional Unit	ICEV	BEV	HFCV	Studies
Bartolozzi et al.	2013	HFCVs and EVs	Tuscany, Italy	Italian electricity mix	kgCO$_2$eq	200 km		35.65	96.38	[7]
				Wind electricity				24.24	33.77	
				Biomass gasification				22.07	53.32	
Yoo et al.	2018	HFCVs	Korea	Natural gas	gCO$_2$eq	km			180–215	[24]
				National grid mix			180–215		388	
Burchart et al.	2018	EVs	Poland and the Czech Republic	Poland 2015	kgCO$_2$eq	150,000 km	42,614	41,453		[8]
				Czech Republic 2015				32,100		
				Poland 2020–2050				25,837–40,887		
				Czech Republic 2020–2050				19,910–32,170		
Qiao et al.	2019	EVs	China	National grid mix 2015	tCO$_2$eq	vehicle	50	41		[11]
				National grid mix 2020				34.1		
Rosenfeld et al.	2019	EVs, ICEVs (SUV cars)	EU	EU28 mix	gCO$_2$eq	pkm	146–225	121	38	[27]
				Wind electricity				42		
Ren et al.	2020	HFCVs	China	Hydropower	gCO$_2$eq	km			61.2	[12]
				Nuclear					129.48	
				Natural gas					187.29–235.35	
				National grid			200.51–247.29	171.84	457.29–495.98	
Wang et al.	2020	HFCVs	China	Natural gas	gCO$_2$eq	km			173	[28]
				Renewable electricity					35	
				Grid mix			309		431	
Zeng et al.	2021	BEVs, PHEVs	China	Chinese grid mix	gCO$_2$eq	km	>200	156		[16]
Sinha	2021	HFCVs	USA	100% RE	gCO$_2$eq	vkm		105		[14]
				75% RE				149		
				California grid				132		
Shafique et al.	2022	EVs, ICEVs	Hong Kong	National grid mix 2019	kgCO$_2$eq	150,000 km	36,000–42,000	32,000		[18]
				National grid mix 2050				15,000		
Shafique and Luo	2022	BEVs	China	China 2019	tCO$_2$eq	150,000 km		42		[13]
				Sweden 2019				13.2		
				Korean 2025				35.47		
				Norway 2030				13.25		
				Sweden 2030				13.29		
				China 2030				21		
Buberger et al.	2022	Passenger cars	Global	Conventional	kgCO$_2$eq	230,000 km	26,754–49,559	17,497	19,740	[29]
				Renewable				5492		

Meanwhile, there is no consensus on other non-GHG air emissions and their relevant impacts deriving from BEVs, HFCVs and ICEVs. EVs are reported to emit 127–234 kgSO_2eq per 150,000 km, which is a much higher acidification impact than ICEVs, at 107 kgSO_2eq [8]. However, Croci et al.'s study indicates a contradicting result, in which BEVs reduce acidification impact by 15–25% compared to diesel vehicles [10]. A higher particulate matter formation in EVs (at 58–90 kgPM10eq per 150,000 km) compared to ICEVs (at 51 kgPM10eq per 150,000 km) is reported in [8], and similar results of 52 kgPM2.5eq emissions per 150,000 km from EVs compared to 41–48 kgPM2.5eq emissions per 150,000 km from ICEVs in [18]. Moreover, EVs increase particulate matter formation by 14% [10]. If future electricity grid mix is applied, by 2050, the particulate matter formation impact of EVs (ranging from 53 to 88 kgPM10eq per 150,000 km) will be still higher than those of ICEVs [8]. In contrast, the impact of EVs (at 22 kgPM2.5eq per 150,000 km) is lower than that of ICEVs in [18], in the same period.

The existing literature indicates that there is a close link between the energy/electricity consumption and the life cycle GHG (and other air) emissions of the alternative and conventional transportation systems. In some cases, due to the fossil fuel-oriented electricity mix, the alternative transportation systems are no longer an "environmentally-friendly" choice. Moreover, most of the current studies were conducted in the EU, USA and China. There are no similar studies being conducted in Vietnam. Considering the fact that the electricity mixes used for charging BEVs or for manufacturing hydrogen of HFCVs are different among countries, it is necessary to implement similar studies in other Asian developing countries such as Vietnam.

This paper compares life cycle energy consumption and air emissions of BEVs, HFCVs and ICEVs in Vietnam. The selected product systems are the battery electric bus (e-bus), the hydrogen fuel cell bus (hydrogen bus) and the diesel bus. The bus fleets in Vietnam were selected in this case study, with the aim of verifying the life cycle impacts of alternative low-carbon transportation systems in developing countries. Moreover, the manufacturing of batteries for EVs is expected to move from China to Vietnam. The largest EVs manufacturer in Vietnam, Vinfast, has recently signed an agreement with its Chinese business partner, Gotion High-tech, to construct a lithium iron phosphate (LIP) battery production plant in Vietnam [30]. The localization of the EV supply chain, on one hand, reduces the impacts of transportation during the manufacturing stage of EVs, and brings local economic benefits. On the other hand, the shift of LIP battery manufacturing from China to Vietnam may cause some problems for the local environment due to the significant life cycle environmental impacts of battery manufacturing [31,32].

The current Vietnamese policy aims at reducing the GHG emissions from the transportation sector by converting energy vector use, e.g., shifting to electric vehicles, biofuel for transportation in replacement of fossil fuels; and shifting modes of transportation, e.g., promoting public transportation [33,34]. The deployment of alternative low-carbon transportation systems, such as e-buses and hydrogen buses, has the double benefits of converting the energy vector use and promoting the public transportation. The diesel buses are widely available in Vietnam, and the e-buses have been recently commercialized in Hanoi, Ho Chi Minh and Phu Quoc. The utilization of e-buses is expected to partly replace the conventional buses, in order to reduce the carbon intensity and energy consumption of the transport sector [35,36].

The data on both e-bus and diesel bus were taken from on-site data of buses being deployed in Hanoi, Vietnam, because at the time the study was conducted, e-buses were only piloted in Hanoi. The data on hydrogen bus were harmonized from the literature, as there is currently no hydrogen bus being deployed in Vietnam. The findings will support the development of national strategies on reducing GHG emissions in the transportation sector and improving air quality in cities. It is also quantitative and scientific-based evidence for verifying whether alternative bus options such e-buses and hydrogen buses in the Vietnamese context are cleaner forms of transportation as compared to conventional public transportation fleets over their whole life cycles.

2. Materials and Methods

The study uses life cycle assessment (LCA) for quantifying and assessing life cycle energy consumption and air emissions of BEVs, HFCVs, and ICEVs, following the guidelines of ISO 14040:2006 and ISO 14044:2006 [37,38]. The assessment was conducted with SimaPro software and DataSmart life cycle inventory database package [39,40].

For the BEVs and ICEVs, product systems are the actual e-bus and diesel bus fleets which are currently operating in Hanoi, Vietnam. The results obtained for e-bus and diesel bus were compared with the life cycle energy consumption and air emissions of HFCVs of the existing literature. The functional unit is one passenger km (one pkm). No allocation was needed, and several assumptions were made during the assessment. They are presented in the following parts.

The study covers the whole life cycle of the product system from well to wheel, including seven stages of bus production, road construction, fuel production/electricity generation, bus operation, road operation and maintenance, disposal of bus and disposal of road. In the case of an e-bus, energy consumption and air emissions due to the construction and operation of charging stations are included, while those of gasoline stations are excluded from the diesel bus's system boundary. Figure 1 presents the system boundary related to the bus life cycle.

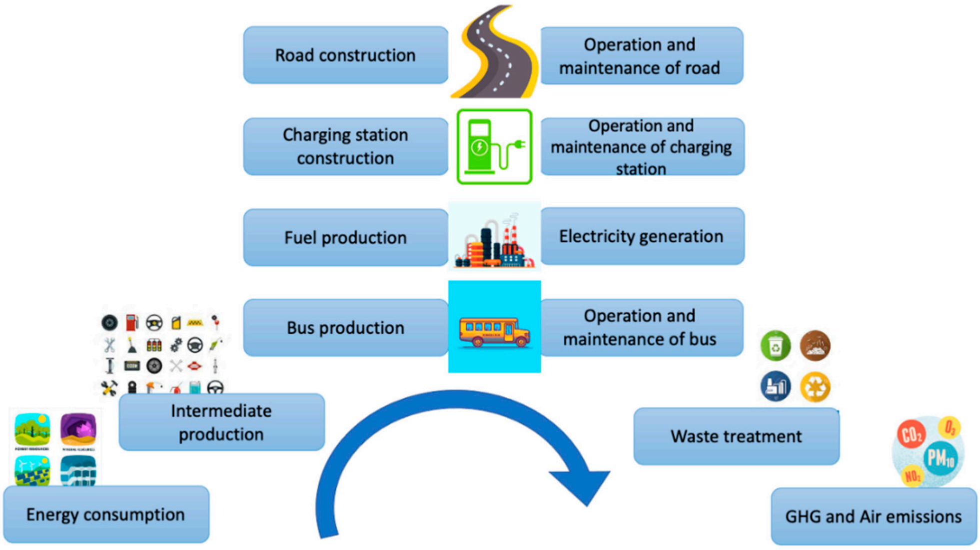

Figure 1. System boundary of the bus product system.

2.1. Bus System Specifications

Buses are the main public transportation mode in cities in Vietnam. This public transportation system is available in 55 out of 63 provinces in Vietnam. The number of buses has increased quickly during the last 10 years from 8400 buses in 2012 to 12,000 buses in 2018, with an annual growth rate of 6% in the same period. Most of the buses are concentrated in the biggest cities of Vietnam such as HCM City, Hanoi, Da Nang, Hai Phong and Can Tho. The total number of buses in Hanoi is 2174, with 95% of buses powered by diesel. A very small number of buses are powered with CNG (102 buses).

In 2021, the first e-bus lines were commercialized in Hanoi. There are 200 e-buses, with a capacity of 68 passengers per bus. These e-buses run on 10 routes, with the total length of 220 km. There are 22 charging stations in the bus depot, with fast-charging technology. It takes about two hours to fully charge a bus for running from 160–220 km [36,41].

The average lifetime for conventional buses in Vietnam ranges from 8 to 12 years, depending on the capacity of the bus. In combination with the actual number of buses in Hanoi, Vietnam (406 large, over-80-passenger buses, 1388 medium, 60-passenger buses, and 308 small, 40-passenger buses), the average lifetime of diesel buses is calculated to be 8 years. The average lifetime of an e-bus is assumed to be 8 years. Similarly, the average vehicle mileage of a conventional bus is 450,320 km. The average e-bus mileage is assumed to be similar to that of a medium 60-passenger diesel bus, at 320,000 km.

The load factor is an important element to show the efficiency of the transportation system. It is calculated by dividing the total length of travel of all passengers (in pkm) by the total length of travel of the bus (in km). The load factors are 7.95 for diesel buses and 13.55 for e-buses, which are smaller than that of regular buses in the USA, at around 14 (calculated with DataSmart database) [40], and larger than that of local buses in the United Kingdom, at 7.2 [42]. Information on e-buses, diesel bus, bus routes and passengers' travel are presented in Table 2.

Table 2. General information on e-buses and diesel buses in Vietnam.

	Unit	E-Bus	Diesel
Number of vehicles		200	2174
Lifetime	year	8	8
Vehicle mileage	km	320,000	450,320
Number of stops		29	3813
Number of bus routes		10	136
Total length of bus routes	km	220	4873.3
Average number of passengers per bus travel	passenger	17.8	17.76
Average length of travel	km	7.68	7.66
Load factor	pkm per km	13.55	7.95

2.2. Vietnam Power System

By 2018, the Vietnam electricity production mix was mainly dominated by large hydropower (40%), coal (38%), gas and oil power (18.7%) [43]. These primary sources were expected to retain in the medium term. However, the large and medium hydro resources have been exploited and the domestic coal is insufficient to supply the existing power plants. This leads to the further development on other types of RES power, which are plentiful in term of technical potential and competitive in term of economic feasibility [43]. By the end of 2020, the shares of hydropower, coal, gas and oil power were reduced and have been replaced by other RES. At this time, the total installed capacity reached 69.3 GW, with 30% of hydropower, 31.1% of coal-fired power and 12.8% of gas and oil power. The remaining electricity came from RES including wind, solar and biomass power [44,45].

2.3. Bus-Related Stages

During the operation of the buses, fuels and electricity are consumed to power the buses. For e-buses, the electricity consumption is around 1.15 to 1.36 kWh/km depending on the loading level (without or with passengers) [36]. For diesel buses, the average diesel consumption is 0.26 L/km, or 0.22 kg/km. Furthermore, the bus operation causes air emissions due to the combustion of diesel for running the diesel bus, while there is no air emission during the operation of e-buses.

During the bus maintenance, electricity is used for running the device and equipment during the maintenance stage, and diesel is consumed for testing the diesel bus during the maintenance. There are emissions to the air related to the use of detergents and replacement of components of the bus. Data on emissions during bus maintenance and fuel/electricity consumption for bus maintenance and reparation are taken from the Datasmart database for electric passenger cars, with some adaptation to the local context [40]. This database is based on EcoInvent database version 2, with updated data on USA and China energy and electricity-related product systems [40].

Both diesel buses and e-buses are manufactured or assembled in Vietnam; however, the access to information is limited. Therefore, Datasmart database for the manufacturing processes of regular buses and electric passenger cars was adapted to the local context.

2.4. Fuel and Infrastructure-Related Stages

Data of fuel-related stages such as diesel production and electricity generation were based on Datasmart database. GHG emissions related to the use of grid electricity for vehicle charging were revised according to the Vietnamese electricity production mix in 2018 and 2019. The most updated emission factors of the Vietnamese electricity production mix were taken from the Department of Climate Change [46,47].

Data of infrastructure-related stages, including road construction, operation and maintenance were the same for both e-buses and diesel buses, being collected from Datasmart database. Data related to charging stations, for e-buses only, are taken from the available literature [48].

2.5. Impact Assessment Method

For energy consumption, the study uses the cumulative energy demand (CED) method version 1.11. The Intergovernmental Panel on Climate Change (IPCC) 2013 indicator was used for long term (100 years) Global Warming Potential (GWP) of the product systems (IPCC GWP 100a). For impacts related to non-GHG air emissions, ReCiPe 2016 Endpoint (H) version 1.04 was used. This impact assessment method calculates the endpoint impacts of a product system, namely three damage-oriented categories: human health, ecosystem and resource availability. As the study focuses on the air emissions of buses, in relation with urban air quality and human health, only endpoint impacts of human health and ecosystem are presented in this paper. All these impact assessment methods are included in Datasmart package [40].

3. Results

3.1. Energy Consumption

For diesel buses, the crude oil consumption is the largest life cycle energy consumption category, which ranges from 31.32 g to 35.24 g/pkm, depending on different efficiency of the bus. Crude oil is mainly used during the fuel production process, which is ultimately used for the operation of a diesel bus. The crude oil consumption of e-buses is one tenth that of diesel buses, at 3.65 g per pkm. The life cycle consumption of fossil fuels of an e-bus is at 3.16×10^{-1} MJ/pkm, accounting for about 90% of all life cycle energy consumption. The life cycle consumption of fossil fuels of a diesel bus is triple that of an e-bus, at 1.87 MJ/pkm. The life cycle fossil fuel consumption of diesel buses accounts for more than 97% of the life cycle renewable and non-renewable energy consumption. The life cycle energy consumption of an e-bus and a diesel bus is presented in Table 3.

Table 3. Energy consumption of e-bus and diesel bus.

Impact Category	Unit	E-Bus	Diesel Bus	Percentage Difference
Non-renewable, fossil	MJ	3.1696×10^{-1}	$1.8711 \times 10^{+0}$	−83%
Non-renewable, biomass	MJ	3.6625×10^{-6}	2.9918×10^{-6}	22%
Non-renewable, nuclear	MJ	2.5494×10^{-2}	3.5766×10^{-2}	−29%
Renewable, biomass	MJ	1.7612×10^{-3}	1.5276×10^{-3}	15%
Renewable, wind, solar, geothermal	MJ	1.2661×10^{-3}	1.6784×10^{-3}	−25%
Renewable, water	MJ	6.9304×10^{-3}	1.4890×10^{-2}	−53%

Table 3 indicates the energy consumption in terms of renewable (biomass, wind, solar, geothermal, water) and non-renewable (fossil, biomass and nuclear) energy. It can be observed that e-buses are not always the better option, compared to diesel buses. For example, the biomass energy requirement of e-buses is larger than that of diesel buses, for both renewable and non-renewable energy. In the other remaining energy consumption impact categories of fossil fuel, nuclear energy, solar, wind, geothermal and hydro-energy, e-buses are much better than diesel buses, and replacing diesel buses with e-buses helps to reduce energy consumption from 25% to 83%, considering different types of energy.

For a hydrogen bus's life cycle energy consumption, the literature is very limited with two studies from China and one study from the USA. In 2010, the study of [49] estimated an amount of 28.94 MJ of life cycle energy consumption per km. This amount may reduce to 24.58 MJ/km thanks to the higher fuel efficiency. A more recent study reports a much lower amount of energy consumption, at 6 to 11 MJ/km [50]. If the average occupancy rate is 20.29 passengers per bus [51], being the same as that of the USA in 2019, the life cycle energy consumption of a hydrogen bus in China would be estimated at around 0.29 to 0.54 MJ/pkm. This number is similar to the life cycle energy consumption of an e-bus in Vietnam. However, it is much higher than the life cycle energy consumption of a hydrogen transit bus in the USA, ranging from 4.6×10^{-2} to 7.3×10^{-2} MJ/pkm, depending on hydrogen production technologies, vehicle speed and road conditions [52].

3.2. GHG Emissions and Global Warming Potential

The life cycle CO_2 emissions of an e-bus are 105.97 g/pkm, much lower than those of a diesel bus, at 144.13 g/pkm. Two thirds of the life cycle CO_2 emissions originate from the operation of an e-bus. Although there are no direct emissions from fossil fuel combustion, the emissions of electricity generation as a background process are the key source for life cycle CO_2 emissions of e-buses. For diesel buses, 72.95% of CO_2 emissions originate from operation and 14.00% from maintenance of the bus. The life cycle GHG emissions of an e-bus is 108.11 gCO_2eq/pkm, which is much lower than that of a diesel bus, at 150.72 gCO_2eq/pkm. For both an e-bus and a diesel bus, the life cycle CO_2 emissions accounts up to 97% of the life cycle GHG emissions. The life cycle CO_2 and GHG emissions of e-buses, hydrogen buses, and diesel buses are presented in Table 4.

Table 4. GHG emissions and GWP of e-buses, hydrogen buses and diesel buses.

GHG Emissions	Unit	E-Bus	Hydrogen Bus	Diesel Bus
Carbon dioxide	g	15.09		22.91
Carbon dioxide, fossil	g	90.88		121.21
Global warming, Human health	DALY	1.0067×10^{-7}		1.4089×10^{-7}
Global warming, Terrestrial ecosystems	species.yr	3.0377×10^{-10}		4.2515×10^{-10}
Global warming, Freshwater ecosystems	species.yr	8.2987×10^{-15}		1.1614×10^{-14}
IPCC GWP 100a	$kgCO_2eq$	1.0812×10^{-1}	1.87×10^{-2}~1.37×10^{-1}	1.5073×10^{-1}

There is a large difference in the life cycle GHG emissions of hydrogen buses. In 2010, the study of [49] indicated a life cycle GHG emission amount of 1500 to 2800 gCO_2eq/km, or 73.92 to 137.99 gCO_2eq/pkm, with assumed occupancy rate of 20.29 passengers per bus [51]. This number is higher than that of hydrogen bus in the USA, at 18.75 to 118.75 gCO_2eq/pkm in the study of Lee et al. [52]. The wide difference of life cycle GHG emissions of hydrogen buses in both studies is mainly due to the origin of the hydrogen, whether it is produced with the national grid mix, natural gas or renewable energy. The most recent study on hydrogen buses in Taiwan reported the life cycle GHG emissions at 29.17 gCO_2eq/pkm [53].

By comparing the life cycle GHG emissions under different scenarios, it was determined that the diesel buses cause significantly higher GWP than the e-buses as well as the hydrogen buses.

Apart from IPCC GWP 100a impact (being quantified in $kgCO_2eq$), the GWP of buses are presented in forms of impacts on human health, terrestrial ecosystem, and freshwater ecosystem. The GWP impacts on human health are measured by the burden of disease caused by global warming, using the unit of disability adjusted life year (DALY). One DALY equals to the loss of one year of full health [54]. The GWP impacts on the terrestrial ecosystem and freshwater ecosystem are measured by species year (species.yr), or the loss of local species over one year [55]. For all three areas of protection including human health, terrestrial ecosystem and freshwater ecosystem, the GWP impacts of e-buses are lower than those of diesel buses. Table 4 summaries the GWP impacts of e buses, hydrogen buses and diesel buses.

During the life cycle of an e-bus, most of the GHG emissions originate from the operation and production of the e-bus. These two stages account for 72.74% and 10.08% of the total emissions, respectively. The emissions from e-bus maintenance, road-related activities, and charging stations account for 3% to 5% of the life cycle emissions. The emissions from end-of-life activities (disposal of the e-bus and road) are negligible. It should be noted that there are no direct emissions during the operation of an e-bus. The large shares of an e-bus operation out of these four impact indicators originate from the indirect emissions of electricity consumption, which accounts for up to 81% of the life cycle GHG emissions. This is due to the high share of fossil fuels in the electricity grid mix. If a cleaner mix of electricity is used for running the bus, the carbon footprint of an e-bus as well as the share of e-bus operation out of total life cycle climate change-related impact will be reduce, and vice versa.

Among the life cycle stages of a diesel bus, the operation and maintenance of the bus contributes to more than 72.53% and 13.57% of the life cycle GHG emissions, respectively. The production of the bus accounts for about 7% of the life cycle GHG emissions. Emissions from the construction, operation and maintenance of roads, as well as emissions from end-of-life stages (disposal of the bus and disposal of the road), are negligible. Each of these stages contributes to less than 4% of the bus's carbon footprint.

Similar to e-buses, the majority of the life cycle GHG emissions over the lifetime of the hydrogen buses come from the extraction and production of hydrogen. Chang and Huang conducted an LCA on conventional buses, e-buses and hydrogen buses in Taiwan [56]. The system boundary includes fuel production/consumption, production of maintenance parts and end of life treatment. Considering hydrogen buses, it is concluded that the hydrogen production stages account for 93.45% of the hydrogen buses' carbon footprint over the studied life cycle [56]. In addition, hydrogen buses emit zero GHGs during bus operation, allowing them to reduce GHG emissions by 100% compared to conventional buses in the wheel to wheel stage [56]. Nonetheless, electricity for hydrogen production is still sourced from the national grid mix, with coal as the primary resource, or hydrogen produced by reforming natural gas. Both processes produce substantial amounts of GHGs.

Figure 2 shows the reduction in life cycle GHG emissions of different bus fleets in percentages. The life cycle GHG emissions of a diesel bus is the reference case (100%). The grey blocks represent the carbon reduction of an e-bus, compared to the GHG emissions of a diesel bus. The carbon reduction of an e-bus is at 28.27% per pkm. Emissions during different life cycle phases of buses are presented in different colors. Except from road-related stages, which are the same for the two types of buses, and charging station-related stage, which is not available for a diesel bus, the carbon reduction benefit of an e-bus compared to a diesel bus ranges from 21% in bus disposal, 39% in bus operation and more than 250% in bus maintenance. The GHG emissions during bus maintenance significantly decrease thanks to the non-consumption of diesel for testing the operation of the bus.

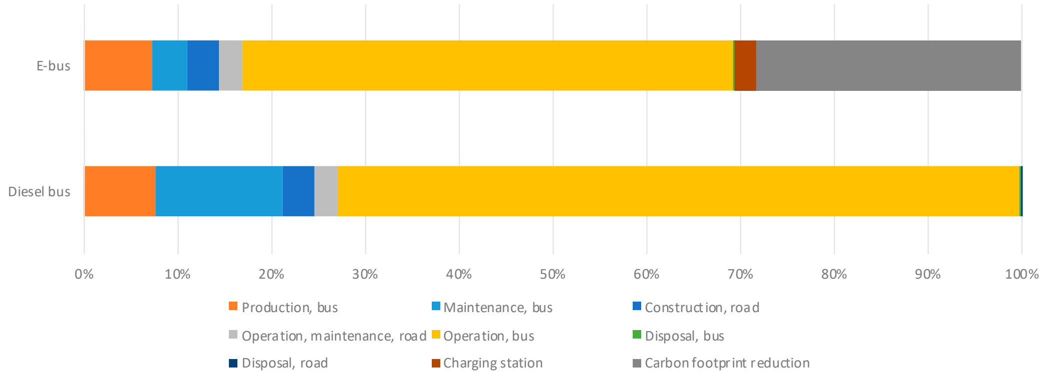

Figure 2. Reduction in carbon footprint of different bus fleets.

3.3. Non-GHG Emission and Air Quality Impacts

Apart from GHG emission reduction benefit, e-buses show some benefits in improving air quality over their life cycle. Table 5 presents non-GHG emissions and air quality-related impacts of e-buses and diesel buses. These emission and impact categories include emissions of ozone, nitrogen oxides, nitrogen dioxides and particulate matters of different sizes, and impacts on stratospheric ozone depletion, ionizing radiation, ozone formation, and human toxicity. Regarding these reported non-GHG emissions and air quality impacts, an e-bus is a better choice than a diesel bus. Specifically, the obtained results indicate 40% of ozone emission reduction, 84% of nitrogen oxides emission reduction, and 34% of nitrogen dioxide emission reduction in e-buses compared with diesel buses. Other e-bus air emissions related to human health reduce correspondingly, at 90% of stratospheric ozone depletion, 35% ionizing radiation, 78% of ozone formation, 13% of human carcinogenic toxicity and 63% of human non-carcinogenic toxicity. The particulate matter of e-buses are also significantly lower than those of diesel buses, ranging from 10–63% emission reduction, depending on the different types of particulate matter. E-buses help to reduce the fine particulate matter formation impact by 64% (refer to Table 5).

Table 5. Non-GHG emissions and air quality impacts of e-buses and diesel buses.

Impact Category	Unit	E-Bus	Diesel Bus	Percentage Difference
Ozone	µg	36.47807	60.74405	−40%
Nitrogen oxides	mg	57.01827	349.69279	−84%
Nitrogen dioxide	ng	69.82419	106.49188	−34%
Stratospheric ozone depletion	DALY	3.0631×10^{-12}	3.0446×10^{-11}	−90%
Ionizing radiation	DALY	1.6227×10^{-11}	2.5067×10^{-11}	−35%
Ozone formation, Human health	DALY	8.3799×10^{-11}	3.7624×10^{-10}	−78%
Human carcinogenic toxicity	DALY	1.3929×10^{-8}	1.6008×10^{-8}	−13%
Human non-carcinogenic toxicity	DALY	2.9267×10^{-9}	7.8881×10^{-9}	−63%
Particulates, unspecified	µg	9.629444	14.6797452	−34%
Particulates, >2.5 um, and <10 um	mg	17.38581	19.38486	−10%
Particulates, >10 um	mg	23.81534	28.64342	−17%
Particulates, <2.5 um	mg	12.92694	35.25257	−63%
Particulates, <10 um	µg	2.298312	3.505255	−34%
Fine particulate matter formation	DALY	2.5793×10^{-8}	7.1978×10^{-8}	−64%

To the best of the authors' knowledge, only Bartolozzi et al.'s study has compared air quality impacts of BEVs and HFCVs over their life cycle [7]. The impacts were calculated for 200 km travel of EVs in Tuscany, Italy, with various electricity supply scenarios, including the national electricity mix, electricity from wind and electricity from biomass gasification (refer to Table 6). It was identified that the HFCVs have higher photochemical oxidation and ozone layer depletion than BEVs in cases when the national grid's electricity and wind electricity is utilized. Specifically, the photochemical oxidation of HFCVs is twice that of BEVs and the ozone layer depletion of HFCV is ten times that of BEVs in the case of using the Italian electricity mix for charging the vehicles and producing hydrogen. If wind electricity, instead of the national grid mix, is used for producing hydrogen, the photochemical oxidation impact of HFCVs reduces from 21 gC_2H_4eq to 9 gC_2H_4eq. This number is slightly higher than that of BEVs, at 8 gC_2H_4eq, with wind electricity for charging the vehicles. In the case of using electricity from biomass gasification, the ozone layer depletion impact of HFCVs is still larger than that of BEVs, at 0.13 gCFC-11eq compared to 0.01 gCFC-11eq. However, in these electricity supply scenarios, both types of EVs bring the benefit of emission absorption, in which HFCVs help to reduce 56 gC_2H_4eq, higher than BEVs, at 14 gC_2H_4eq [7].

Table 6. Some air quality impacts of e-buses and hydrogen buses [7].

Impact Categories	Unit	Functional Unit	EVs	Electricity Sources		
				Italian Electricity Mix	Wind Electricity	Biomass Gasification
Photochemical oxidation	kgC_2H4eq	200 km	BEVs HFCVs	1.00×10^{-2} 2.10×10^{-2}	8.00×10^{-3} 9.00×10^{-3}	-1.40×10^{-2} -5.60×10^{-2}
Ozone layer depletion	kgCFC-11eq	200 km	BEVs HFCVs	1.86×10^{-5} 1.04×10^{-4}	1.84×10^{-5} 1.35×10^{-4}	1.78×10^{-5} 1.38×10^{-4}

4. Carbon Footprint Comparison of Buses in Vietnam and Globally

The literature on e-buses' LCA is limited, even for GHG emissions, which typically attracts a lot of attention from scientists. The study of Ou et al. was the first LCA on bus fleets, which estimated life cycle GHG emissions of different bus alternatives, such as those fueled with gasoline, diesel, liquefied petroleum gas (LPG), compressed natural gas (CNG), hydrogen, methanol, dimethyl ether and electricity in the Chinese context [49]. It is identified that the life cycle GHG emissions of an e-bus is 1.5 $kgCO_2eq/km$, which is lower than that of a gasoline bus or a diesel bus, from around 1.75 $kgCO_2eq/km$ to 1.85 $kgCO_2eq/km$ [49]. In 2013, Cooney, Hawkins and Marriott compared conventional buses and e-buses in the USA. The authors find that the conventional buses seem to be the better choice over e-buses with the existing average USA grid mix. E-buses show a better life cycle GHG emission profile in only eight states of the USA [48].

Recently, the updated literature for LCA on bus fleets pointed out that the electrification of buses is a better choice in terms of GHG emission reduction benefit. Nordelöf, Romare and Tivander conducted an LCA on Volvo e-buses in Sweden. The study indicated that the life cycle GHG emissions range from 16 to 60 gCO_2eq/pkm for e-buses, depending on different electricity mixes [57]. The emissions were the smallest with Sweden's electricity grid and the highest with the US electricity mix. With the EU electricity mix, the Swedish e-bus emitted 48 gCO_2eq/pkm.

In the Norwegian context, Lie et al. compared the life cycle GHG emissions of hybrid, and plugin hybrid e-buses and conventional buses and identified that e-buses emitted 78% less GHGs than conventional diesel buses over their life cycle [17]. The GHG emission of that e-bus being powered by Norwegian electricity is between 26–79 gCO_2eq/pkm. The same e-bus, powered with Nordic or EU grid mix, emitted 32 and 55 gCO_2eq/pkm, respectively. In the case that e-bus fleets replaced the existing bus fleets, the total GHG emissions might be reduced by up to 61% [17].

In other EU countries, the life cycle GHG emissions of e-buses range between 10–36 gCO_2eq/pkm [58,59]. Moreover, diesel buses in these countries emit much less GHG over their life cycle compared to those in Vietnam, at around 34 gCO_2eq/pkm compared to 150 gCO_2eq/pkm. Table 7 compares the carbon footprint of different bus fleets in Vietnam and globally.

Table 7. Carbon footprint of bus fleets in Vietnam and globally.

Carbon Footprint (gCO_2eq/pkm)	Electricity Mix	E-Bus	Conventional Bus	Study
Vietnam	Vietnam	108.11	150.73	This study
Spain	Spain	10	34	[58]
EU	EU-28, France, Germany, Italy	11–36		[59]
Sweden	Sweden, EU or USA	16–60	94	[57]
Norway	Norwegian, Nordic or EU	26–79	66–105	[17]

Table 7 indicates that the GHG emissions of e-buses which are currently operating in Vietnam is much lower than those of diesel buses in the same context. However, the GHG emissions of Vietnamese e-buses are similar to those of conventional buses in some EU countries, and much higher than those of e-buses in these countries. In order to further decarbonize the public transportation systems of Vietnam, it is recommended to reduce the carbon footprint of the electricity grid, as the electricity consumption during the operation of e-buses contributes up to 72% of the life cycle GHG emissions of an e-bus. For example, if the Vietnamese electricity grid is developed towards more RES and higher efficiencies, similar to the USA or EU average grid mix, the carbon footprint of e-buses will range from 55.1 to 99.4 gCO_2eq/km. Another option is using renewable electricity, for example solar power, for charging the e-buses. In this case, the carbon footprint of Vietnamese e-buses may reduce to 38.1 gCO_2eq/pkm, similar to that of e-buses in Sweden or Norway.

5. Conclusions

The LCA was carried out from cradle to grave for e-buses and diesel buses in Vietnam, and compared them with hydrogen buses in terms of energy consumption and air emissions. The results indicate that the environmental profile of an e-bus is better than a diesel bus over its whole life cycle in both energy consumption and air emissions. Replacing a diesel bus with an e-bus can reduce energy consumption by 50%, GHG emissions by 39%, and 13% to 90% of other impacts related to air quality. Comparing Vietnamese e-buses and hydrogen buses elsewhere, it is not clear whether an e-bus or a hydrogen bus is the better option, due to the considerable dependence on hydrogen production technologies and operational conditions.

The life cycle energy consumption and air emissions of an e-bus as well as of a hydrogen bus depend on the electricity supply, for charging the e-bus and for producing hydrogen. The emission intensity of grid electricity is closely related to the share of fossil fuels and renewables in the supply mix, and the efficiency of the generation, transmission and distribution systems. Although the producer and operator of e-buses have limited control on the grid, it is their choice to buy the green certified electric power. On one hand, their choice of the green certified electric power will reduce the GHG emissions of alternative transportation systems. On the other hand, it would further affect the electric power market and enhance the investment on the greener power generation technologies, such as renewable power. The promotion of alternative transportation systems will have the dual impacts of reducing (or increasing) the life cycle impacts of both transportation sector and power sector. In any case, in order to achieve the “greener” transportation sector, a higher share of renewables in the electricity mix is needed. This will require the active and collaborative engagement of key players in both the transportation sector (bus producers and operators) and the energy/power sector (power suppliers and grid operators).

The study limits in the reviews on energy consumption and air emissions of global hydrogen buses, due to the fact that there is no hydrogen bus being currently deployed in Vietnam. In fact, there is a substantial amount of renewable power in the central and the southern parts of Vietnam, which are not allowed to be connected to the grid, due to the low flexibility of the grid infrastructure. The excess renewable power may be used for producing hydrogen. In this case, the deployment of hydrogen buses and FCEVs in Vietnam can bring the co-benefits of reducing the carbon footprint of the transportation sector, as well as solving the problem of excess renewable power of the power sector. Therefore, the future work should extend to the contribution of hydrogen buses and FCEVs in transitioning to the sustainable energy. Moreover, the study does not include a detailed calculation for battery production for e-buses in local contexts. The battery production and its end-of-life management are potential sources of air emissions, which should be taken into account in the future studies for a more holistic impact assessment of alternative vehicle in Vietnam as well as in other countries.

This LCA study of alternative low-carbon buses will enhance the environmental awareness among bus enterprises. The customers are now becoming more and more conscious of better air quality, less fossil fuel consumption and healthier environment. In response to the customers' demand, the producers and retailers are required to provide more environmentally friendly products and services. In the case of e-bus and hydrogen bus production and operation, this will promote the use of cleaner forms of transportation. In the long term, it is expected to support the agreement on an environmental labelling of low-carbon transportation systems.

In terms of life cycle energy use and air emissions, the study indicates the important contribution of the transportation sector in the GHG as well as non-GHG emissions, and its role in fighting climate change and improving urban air quality by shifting from the conventional transportation system into a low-carbon system.

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