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Comparative life cycle analysis of selected bus drive systems

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ABSTRACT

The modern means of transport sector is faced with the need to adapt to the requirements of sustainable development. There is a need to reduce the negative impact on the environment and consider social as well as environmental aspects. This transformation requires not only the implementation of new technologies, but also a comprehensive approach to their life cycle assessment. With these assumptions in mind, this article conducted a comparative analysis of two types of buses used in public transport – with a diesel engine (ICEV-D) and with a fuel cell drive (FCEV), considering both current operating conditions and forecasts for 2050. The life cycle assessment (LCA) was carried out using SimaPro software. The research results indicate that FCEV buses have the potential to significantly reduce the harmfulness of operating city buses compared to ICEV-D. The total negative impact on the environment in the life cycle of FCEV buses depends primarily on the method of hydrogen production, and the main challenge remains the high energy consumption of its production processes.

Keywords: drive systems, life cycle assessment, ICEV-D, FCEV, electromobility.

INTRODUCTION

The dynamic development of the means of transport sector recorded in recent decades is an important factor in global economic development, but at the same time it is also a significant source of destructive impact on the environment, generating nuisances and problems that are particularly significant on a local scale, especially in urban agglomerations (1, 2). Undesirable effects concern not only the natural environment, but also society, which the development of this sector has allowed crossing a key barrier of civilization development. However, these effects vary depending on the level of economic development, advancement and use of different modes of transport, location (including climate) and the specific sensitivity of individual elements of the environment (3–5). Operated means of transport are one of the causes of environmental degradation and has a negative impact on human health. In Europe, it is the source of almost half of total nitrogen oxide emissions, about 45% of carbon monoxide, about 40% of tropospheric ozone precursors, about 20% of PM10 and about 30% of PM2.5 (particulate matter with a diameter of 10 and 2.5 μm), about 20% of NMVOCs (non-methane volatile organic compounds), about 25% of CO_2 emissions and about 20% of other greenhouse gases (3, 6).

The implementation of advanced technologies in the means of transport sector should not increase harmful emissions across the entire life-cycle of vehicles, including urban buses (7, 8). It is therefore reasonable to conduct an analysis of which types of buses and fuel technologies used contribute the most to reducing the impact on the environment, in particular reducing CO_2 emissions and other pollutants generated at each stage of their life. This assessment should consider not only emissions directly from the exhaust system, but also those related to the production of fuel and electricity, vehicle manufacturing, their use as well as processes related to the end of their life.

In connection with the above, a decision was made to conduct detailed research using the life cycle assessment (LCA) approach, the aim of which was to assess both the overall impact on the environment of the two most important buses (with a combustion engine powered by diesel oil, and electric buses with fuel cell drive) and the individual stages of their life cycles (manufacturing, operation divided into well-to-tank (WTT), tank-to-wheel (TTW) and maintenance, as well as post-consumer management in the form of recycling (Figure 1). Additionally, changes in technology and energy mixes in the period from 2020 to 2050 (forecasts) were considered. The conducted analyses combined theoretical and literature knowledge with practical knowledge and data obtained from manufacturers. This made it possible to propose a comprehensive methodology for assessing the environmental footprint of technical objects on the example of city buses.

In 2024, the bus fleet used in public transport in Poland included about 13 thousand vehicles (Figure 2). Among them, zero-emission buses have an increasing share. Electric vehicles accounted for about 9% of the entire fleet, or almost 1300 units. Hydrogen buses, although still few in number, were represented by about 60 units. Their number is systematically growing along with the growing interest of local governments in the solutions that help improve air quality and reduce emissions (9).

In the available literature, one can already find examples of environmental analyses of means of transport, including buses. Nordelöf et al. (10) compared the life cycle of conventional, hybrid and electric city buses, analysing the impact of the fuel mix (diesel and HVO) and emissions from power generation in Sweden, the EU and the US. The results show that hybrids and electric buses significantly reduce CO_2 emissions when the electricity comes from the grid: less than 200 g CO_2/kWh (for HVO) or 750 g CO_2/kWh (for diesel), despite a higher battery production footprint. Iannuzzi et al. (11) compared diesel city buses with hydrogen variants (PEM fuel cell) for the city of Rosario. They conducted a full life-cycle analysis: from raw material extraction to fuel combustion, considering five hydrogen production methods (three "green" from biomass and two "grey" from natural gas or grid electrolysis). The authors showed that buses with local green hydrogen could reduce CO_2 emissions by ≥ 70 % compared to diesel, meeting the EU requirements. Acar and Dincer (11) showed that hydrogen can become a clean fuel for transport if it is produced from renewable sources. The authors, comparing different drives (conventional, hybrid, electric, biofuels, fuel cell, ICE engine for hydrogen), obtained the highest environmental and energy rating for fuel cell vehicles, just ahead of combustion engines powered by hydrogen; buses with classic fossil fuel engines fared the worst. Grazieschi et al. (12) compared city buses with three drives: diesel, fully electric and hydrogen. Operational data from Bolzano show that an electric bus uses 43% less non-renewable energy and emits 33% less CO_2 than diesel. The hydrogen example brings clear benefits when the hydrogen is produced from renewable energy, almost none when it comes from methane reforming, and even doubles the climate burden when the electrolysis is powered by electricity from fossil fuels. Szczurowski et al. (13) conducted LCA of three city buses (diesel, diesel hybrid, electric) in the realities of Krakow, analysing vehicle production, fuel/energy consumption and

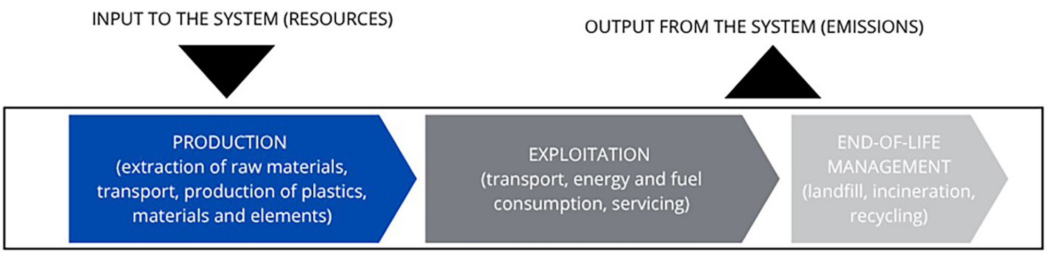

Figure 1. Life cycle stages of city buses

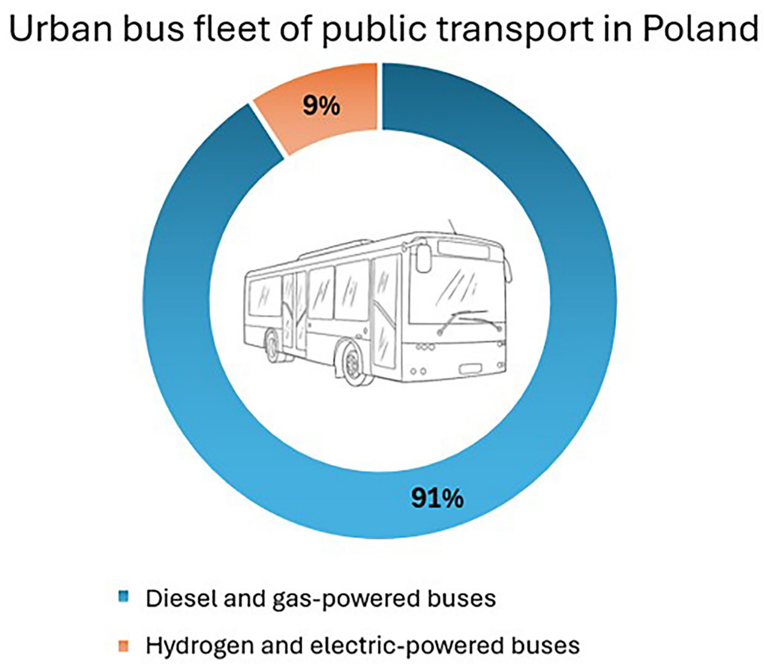

Figure 2. Public transport bus fleet in Poland (data for 2024). Own study based on (9)

the Polish electricity mix until 2040. Using the IMPACT 2002+ method, they assessed the effects on human health, ecosystems, climate and resources. The analysis showed that the more electric buses with low-emission energy, the lower the burden in all categories.

The studies available so far have not considered the simultaneous presentation of the current state and the forecast for mid-century under national conditions. The analysis conducted in this article allows for the assessment of how the development of hydrogen technologies can change the environmental balance in the long term, which was missing in most previous studies focused solely on current conditions, and leads to a detailed assessment of the impact of the hydrogen production method on the full life cycle of city buses. To achieve the main objective of the work, the assessment of the size of the negative impact on the environment in the life cycle of selected city buses was adopted as a criterion - both overall and at individual stages, considering recycling after the end of use. This allowed for indicating the most environmentally friendly processes and identifying the main sources of adverse impacts. On the basis of the analysis of the impacts related to the production, use and management of vehicles, possible directions of actions were determined that can help reduce their harmful impact.

MATERIALS AND METHOD

The study compared two types of buses: with an internal combustion engine powered by diesel oil (ICEV-D) and electric buses with fuel cell drive (FCEV). Objects of similar dimensions (low-floor, standard - without articulations) and identical level of functionality were selected, differentiated in terms of the type of drive used. The basis for the assessment of the life cycle of the vehicles was their total mileage and time of operation, which were the functional reference unit. Therefore, the vehicle-kilometre (vkm) was adopted as the main reference unit. The period of use of the vehicles was determined based on the analyses prepared on behalf of the European Commission. Additional calculation units were used only to obtain partial results (14, 15). The adopted time horizon covered the present day and the year 2050. The main changes included differences in the European energy mix, differences in the energy demand of buses, different supply of conventional and renewable fuels, innovations at the production stage (e.g. plastics and materials used, reducing vehicle weight, new production processes), as well as changes in the impact of the production of plastics and materials (decarbonisation of the energy used).

To determine the environmental impact of the research objects, the SimaPro 9.5 software with the Ecoinvent database (version 3.9) was used. The ReCiPe 2016 method was used in the assessment, within which three main areas of impact were analysed. Compared to other models used in LCIA, ReCiPe 2016 is distinguished by the widest set of midpoint categories. It is a kind of improvement of ReCiPe 2008 and other, previously used models, e.g. CML 2000, Ecoindicator 99 (16). In contrast to the 2008 iteration, the ReCiPe 2016 impact-assessment framework supplies geographically explicit characterisation factors that extend beyond the European context to encompass globally representative values (17, 18). To describe in detail the life cycle of different types of city buses, the widest possible range of data was collected directly from manufacturers. In the case of information gaps, the data was supplemented based on available literature sources.

The electricity and fuel consumption for different types of drive systems was determined mainly based on weighted average registrations of new city buses in 2020. The basic data was taken from official test results, but they were significantly corrected based on reliable databases based on real operating conditions and user experiences. These corrections were crucial to obtain a reliable picture of the actual energy consumption, also considering losses related to the charging process. The verified data, referring to European conditions, are summarized in Table 1 (15, 19–21). Due to the fact that the end-of-use stage, often omitted in life-cycle analyses of means of transport, may have a significant environmental impact, this study assumed a scenario of maximum recycling of materials and components of the assessed buses.

The fuel cycle analysis separately considered the emissions resulting from the consumption of electricity and fuels during vehicle operation. They were divided into the emissions related to the production of energy and fuel (WTT – "from source to tank") and their combustion in the bus (TTW – "from tank to wheel"). For fossil fuels, the entire chain was considered – from oil or gas extraction, through their processing, transport, refining, to distribution. For hydrogen from fossil fuels, the impact of raw material extraction, their processing, transport, coal gasification or gas reforming, and hydrogen compression was assessed.

RESULTS

The ReCiPe 2016 model was used in the initial stage of the environmental footprint analysis. The assessment was carried out in three main impact areas, considering a total of twenty-two impact categories. Only the most significant results were discussed in the doctoral thesis. The results obtained at the characterisation stage were presented in three units: DALY (for the assessment of the impact on human health), species.year (for the assessment of the quality of ecosystems) and USD (for the assessment of the use of natural resources). The greatest negative impact on human health is attributed to the category of toxic substances that do not have carcinogenic properties (Table 2). In the case of the categories affecting the quality of ecosystems, the most harmful were emissions of substances leading to the acidification of terrestrial environments. In the case of the categories related to raw material resources, the greatest environmental burden was found in processes contributing to the depletion of mineral resources.

The results show that by 2050 there is a significant reduction in environmental impacts in almost all categories analysed – reductions of around 30–40% compared to 2020 levels. The largest absolute reductions concern the formation of particulate matter (PM), greenhouse gas emissions affecting human health as well as the consumption of mineral resources and fossil fuels. Despite these improvements, the vehicle use phase (TTW) remains a key 'hot spot': even in the 2050 scenario, bus driving accounts for 60-90% of the total burden in most health and climate categories. Vehicle production still plays a significant role in the context of resource depletion. In terms of mineral resource depletion processes and the processes that deplete fossil fuel resources, its share was 5–10% in 2020; by 2050 it is decreasing but

Table 1. Average actual values of electricity and fuel consumption for city buses. Own study based on (15, 19–21)

Vehicle type	Electricity and/or fuel consumption over the vehicle's life cycle			
	diesel fuel [l]	gas [kg]	electric energy [kWh]	hydrogen [kg]
ICEV-D	270,000	x	x	x
FCEV	x	x	x	54,000

Table 2. Environmental analysis results for ICEV-D

Impact factory	2020					2050					Unit
	Production	WTT	TTW	Maintenance	Recycling	Production	WTT	TTW	Maintenance	Recycling	
Substances that increase global warming and affect human health	9.48×10^{1}	2.14×10^{2}	1.73×10^{3}	6.32×10^{1}	-3.79×10^{1}	7.59×10^{1}	1.33×10^{2}	1.11×10^{3}	2.22×10^{1}	-1.90×10^{1}	DALY
Substances that exacerbate global warming and affect terrestrial ecosystems	2.87×10^{-1}	6.47×10^{-1}	5.24×10^{0}	1.92×10^{-1}	-1.14×10^{-1}	2.30×10^{-1}	4.01×10^{-1}	3.35×10^{0}	6.70×10^{-2}	-5.73×10^{-2}	species.year
Substances that exacerbate global warming and affect freshwater ecosystems	7.82×10^{-6}	1.77×10^{-5}	1.42×10^{-4}	5.21×10^{-6}	-3.13×10^{-6}	6.27×10^{-6}	1.10×10^{-5}	9.12×10^{-5}	1.83×10^{-6}	-1.57×10^{-6}	species.year
Substances that deplete the ozone layer	1.00×10^{-1}	6.17×10^{-2}	1.83×10^{0}	6.70×10^{-2}	-4.06×10^{-2}	8.08×10^{-2}	3.83×10^{-2}	1.17×10^{0}	2.36×10^{-2}	-2.03×10^{-2}	DALY
Substances emitting ionizing radiation	3.22×10^{-2}	4.16×10^{-2}	5.88×10^{-1}	2.15×10^{-2}	-1.19×10^{-2}	2.56×10^{-2}	2.58×10^{-2}	3.76×10^{-1}	7.47×10^{-3}	-6.12×10^{-3}	DALY
Substances inducing the formation of ozone in the troposphere, affecting human health	1.31×10^{0}	1.73×10^{0}	2.38×10^{1}	8.70×10^{-1}	-5.28×10^{-1}	1.05×10^{0}	1.08×10^{0}	1.52×10^{1}	3.06×10^{-1}	-2.64×10^{-1}	DALY
Substances inducing the formation of particulate matter (PM)	6.53×10^{-2}	3.82×10^{2}	1.19×10^{4}	4.35×10^{2}	-2.64×10^{2}	5.23×10^{2}	2.37×10^{2}	7.62×10^{3}	1.53×10^{2}	-1.32×10^{2}	DALY
Substances inducing the formation of ozone in the troposphere, affecting terrestrial ecosystems	1.89×10^{-1}	2.50×10^{-1}	3.45×10^{0}	1.26×10^{-1}	-7.66×10^{-2}	1.52×10^{-1}	1.55×10^{-1}	2.21×10^{0}	4.43×10^{-2}	-3.82×10^{-2}	species.year
Substances causing acidification of terrestrial ecosystems	7.66×10^{-1}	2.35×10^{-1}	1.40×10^{1}	5.10×10^{-1}	-3.10×10^{-1}	6.16×10^{-1}	1.46×10^{-1}	8.93×10^{0}	1.80×10^{-1}	-1.55×10^{-1}	species.year
Substances causing eutrophication of freshwater ecosystems	8.86×10^{-2}	6.79×10^{-2}	1.62×10^{0}	5.91×10^{-2}	-3.59×10^{-2}	7.13×10^{-2}	4.21×10^{-2}	1.03×10^{0}	2.08×10^{-2}	-1.80×10^{-2}	species.year
Substances causing eutrophication of marine ecosystems	8.30×10^{-6}	4.55×10^{-6}	1.51×10^{-4}	5.53×10^{-6}	-3.39×10^{-6}	6.78×10^{-6}	2.82×10^{-6}	9.68×10^{-5}	1.98×10^{-6}	-1.72×10^{-6}	species.year
Ecotoxic substances affecting terrestrial ecosystems	2.64×10^{-3}	9.39×10^{-3}	4.82×10^{-2}	1.76×10^{-3}	-1.06×10^{-3}	2.11×10^{-3}	5.82×10^{-3}	3.08×10^{-2}	6.16×10^{-4}	-5.29×10^{-4}	species.year
Ecotoxic substances affecting freshwater ecosystems	3.68×10^{-2}	5.74×10^{-3}	6.71×10^{-1}	2.45×10^{-2}	-1.49×10^{-2}	2.96×10^{-2}	3.56×10^{-3}	4.29×10^{-1}	8.63×10^{-3}	-7.45×10^{-3}	species.year
Ecotoxic substances affecting marine ecosystems	7.06×10^{-3}	1.16×10^{-3}	1.29×10^{-1}	4.71×10^{-3}	-2.86×10^{-2}	5.67×10^{-3}	7.22×10^{-4}	8.24×10^{-2}	1.66×10^{-3}	-1.43×10^{-3}	species.year
Carcinogenic toxic substances affecting human health	5.10×10^{1}	$6.51E\times10^{1}$	9.30×10^{2}	3.40×10^{1}	-2.04×10^{1}	4.02×10^{1}	4.04×10^{1}	5.95×10^{2}	1.17×10^{1}	-1.01×10^{1}	DALY

Table 2. Cont.

Non-carcinogenic toxic substances that affect human health	4.86×10^{2}	2.05×10^{2}	8.86×10^{3}	3.24×10^{2}	-1.97×10^{2}	3.91×10^{2}	1.27×10^{2}	5.67×10^{3}	1.14×10^{2}	-9.84×10^{1}	DALY
Land use processes	2.93×10^{-2}	1.96×10^{-1}	5.34×10^{-1}	1.95×10^{-2}	-1.18×10^{-2}	2.34×10^{-2}	1.21×10^{-1}	3.42×10^{-1}	6.83×10^{-3}	-5.89×10^{-3}	species.year
Mineral resource depletion processes	2.55×10^{7}	3.14×10^{5}	4.65×10^{8}	1.70×10^{7}	-1.08×10^{6}	2.15×10^{6}	1.95×10^{5}	2.98×10^{8}	6.26×10^{5}	-5.39×10^{5}	USD
Processes that deplete fossil fuel resources	6.34×10^{6}	2.61×10^{7}	1.16×10^{8}	4.23×10^{6}	-2.54×10^{6}	5.12×10^{6}	1.62×10^{7}	7.40×10^{7}	1.49×10^{6}	-1.28×10^{6}	USD
Processes that affect water availability, affecting human health	3.17×10^{1}	7.73×10^{-1}	5.78×10^{2}	2.11×10^{1}	-2.21×10^{1}	1.65×10^{1}	4.79×10^{-1}	3.70×10^{2}	4.80×10^{0}	-4.69×10^{0}	DALY
Processes that affect water availability, affecting terrestrial ecosystems	1.96×10^{-1}	5.34×10^{-3}	3.57×10^{0}	1.31×10^{-1}	-1.33×10^{-1}	1.03×10^{-1}	3.31×10^{-3}	2.28×10^{0}	3.01×10^{-2}	-2.78×10^{-2}	species.year
Processes that affect water availability, affecting aquatic ecosystems	9.27×10^{-6}	7.05×10^{-7}	1.69×10^{-4}	6.18×10^{-6}	-5.75×10^{-6}	5.03×10^{-6}	4.37×10^{-7}	1.08×10^{-4}	1.47×10^{-6}	-1.14×10^{-6}	species.year

still noticeable. This indicates the need for material innovations, such as lighter structures or greater use of recycled materials.

The method of post-consumer management of plastics, materials and elements occurring in the life cycle of the examined buses significantly affects the level of their impact on the environment. Recycling processes enable to largely reduce the size of the negative impact both for currently used buses ($-9.24\cdot10^{6}$ Pt) and those that are to be used in approx. 25 years ($-4.51\cdot10^{6}$ Pt). The highest level of destructive impact on the environment was recorded for the life cycle of buses from 2020, which will not be recycled after the end of their service life ($9.17\cdot10^{7}$ Pt). For all the cases considered, the impact on human health amounted to approx. 97% of the total impacts recorded in the life cycles of the considered vehicles. The highest level of negative impact on human health at the stage of production and service was recorded for sulphur dioxide, arsenic and zinc emissions, while at the WTT and TTW stages – for the processes related to the use of water, carbon dioxide emissions and particles < 2.5 µm (Figure 3).

Table 3 presents the results of the assessment of the environmental impacts in the life cycle of fuel cell electric buses (FCEV) for the considered impact categories. The currently used vehicles generate a greater burden on the environment compared to those expected to be in operation in 2050. The most serious threat to human health is posed by the emissions of substances that promote the formation of particulate matter (PM). In the context of the impact on ecosystems, the most harmful category is related to processes limiting the availability of water for terrestrial environments. In terms of the use of natural resources, the greatest negative effects were recorded for the processes leading to the depletion of fossil fuel resources.

The way in which materials, plastics and components are managed after the end of the bus service life has a significant impact on the overall level of their impact on the environment. The implementation of recycling significantly reduces the negative ecological effects – both in the case of currently used vehicles (reduction by $1.29\cdot10^{7}$ Pt), and those that will be put into operation in about 25 years (reduction by $1.49\cdot10^{6}$ Pt). The highest environmental burden was recorded for buses from 2020, which will not be recycled at the end of their life cycle ($4.46\cdot10^{7}$ Pt). For all cases analysed, approximately 96% of the total life cycle impacts were related to human health impacts (Figure 4).

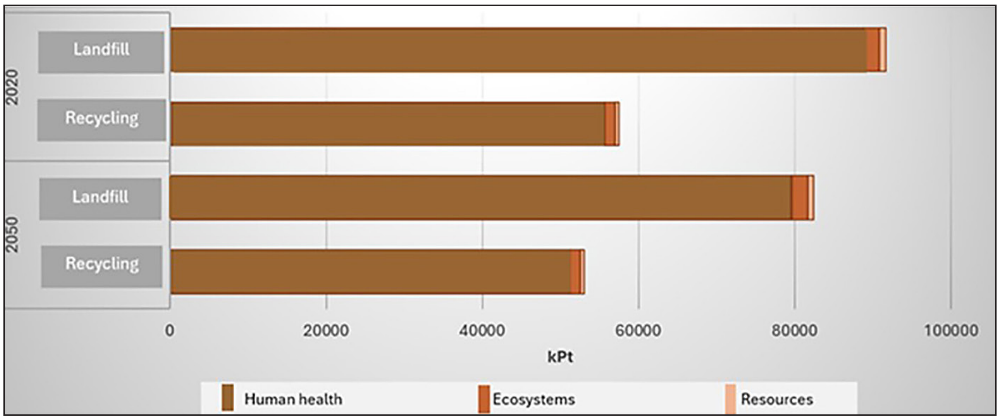

Figure 3. Grouping and weighing environmental impacts in the life cycle of diesel-fuelled combustion engine buses (ICEV-D) for the analysed impact areas, considering different post-consumer management methods (ReCiPe 2016 model, unit: kPt – thousands of environmental points)

DISCUSSION

The highest values of harmful impact in the analysed area were observed in the case of the buses with combustion engines ICEV-D. For vehicles manufactured in 2020, this value was $2.71 \cdot 10^4$ DALY and for buses planned to be in operation in 2050 – $1.73 \cdot 10^4$ DALY. Changing the way ICEV-D buses are powered, e.g. by electricity from renewable sources, would significantly reduce the negative impacts in the considered scope. The implementation of innovative, more sustainable production processes of plastics, materials, components and working units, characterised by lower material and energy consumption, as well as the practical application of the main assumptions of the closed-loop economy, would significantly reduce the destructive impacts in the considered area. In the case of electric the buses with FCEV, the impact of their life cycles differs mainly depending on how the hydrogen necessary for their propulsion was obtained. Currently, it is most often "grey" or "black" hydrogen. The use of "blue" or "green" would significantly reduce the negative impacts on human health in the perspective of the entire life cycle of FCEV vehicles. All buses currently in use are characterised by higher values of adverse health impacts compared to solutions of the same type, which are to be included in the fleet in approx. 25 years. The life cycle stages with the highest levels of adverse impacts in this area are TTW for ICEV-D and WTT for FCEV. The operation of fuel cell electric buses registered in 2020 is characterised by the generation of more greenhouse gases than those emitted during the production stage. If they were powered by "blue" or "green" hydrogen, their negative impact on the environment would be significantly reduced.

In the ecosystems category, the maximum value of the destructive impact in this area was observed for ICEV-D buses (2020: 3.33×10^1 species.year, 2050: 2.12×10^1 species.year). In this case, the stage of the life cycle with the highest level of negative impact was also TTW (2020: 2.92×10^1 species.year, 2050: 1.87×10^1 species.year) constituting approx. 88% of all impacts. The use of non-renewable energy sources is inextricably linked to the emission of several substances into the environment that cause a decrease in the quality of ecosystems. As shown by the conducted studies, all buses currently in use are characterised by higher values of undesirable impact on ecosystems compared to the vehicles of the same type that are to be used in 2050. The stages of the life cycle characterised by the highest level of harmful impact in the studied scope include production for FCEV and ICEV-D from 2050 and TTW for ICEV-D from 2020.

The use of FCEV can significantly contribute to reducing the harmfulness of the means of transport in the coming years, especially in the context of the transformation of transport systems towards low-emission solutions. These vehicles, using hydrogen as fuel, do not emit pollutants during use, and the only product of the reaction in the fuel cells is water vapour (22, 23). However, the total level of harmful emissions associated with the FCEV life cycle depends mainly on the method of hydrogen extraction. In the case of hydrogen produced from fossil fuels,

Table 3. Environmental analysis results for FCEV

Impact category	2020					2050					Unit
	Production	WTT	TTW	Maintenance	Recycling	Production	WTT	TTW	Maintenance	Recycling	
Substances that increase global warming and affect human health	1.10×10^{2}	3.47×10^{2}	x	2.90×10^{1}	-2.62×10^{1}	8.09×10^{1}	4.85×10^{1}	x	1.62×10^{1}	-6.54×10^{0}	DALY
Substances that exacerbate global warming and affect terrestrial ecosystems	3.31×10^{-1}	1.05×10^{0}	x	8.77×10^{-2}	-7.91×10^{-2}	2.45×10^{-1}	1.47×10^{-1}	x	4.89×10^{-2}	-1.97×10^{-2}	species.year
Substances that exacerbate global warming and affect freshwater ecosystems	9.04×10^{-6}	2.87×10^{-5}	x	2.39×10^{-6}	-2.16×10^{-6}	6.74×10^{-6}	4.02×10^{-6}	x	1.35×10^{-6}	-5.39×10^{-7}	species.year
Substances that deplete the ozone layer	4.28×10^{-2}	1.34×10^{0}	x	1.13×10^{-2}	-1.24×10^{-2}	3.77×10^{-2}	1.88×10^{-1}	x	7.53×10^{-3}	-3.33×10^{-3}	DALY
Substances emitting ionizing radiation	6.90×10^{-2}	2.11×10^{-1}	x	1.83×10^{-2}	-3.72×10^{-3}	4.29×10^{-2}	2.95×10^{-2}	x	8.57×10^{-3}	-1.20×10^{-3}	DALY
Substances inducing the formation of ozone in the troposphere, affecting human health	2.41×10^{-1}	9.02×10^{-1}	x	6.39×10^{-2}	-6.19×10^{-2}	1.65×10^{-1}	1.26×10^{-1}	x	3.30×10^{-2}	-1.34×10^{-2}	DALY
Substances inducing the formation of particulate matter (PM)	1.33×10^{2}	4.12×10^{2}	x	3.52×10^{1}	-3.31×10^{1}	8.52×10^{1}	5.76×10^{1}	x	1.70×10^{1}	-6.77×10^{0}	DALY
Substances inducing the formation of ozone in the troposphere, affecting terrestrial ecosystems	3.51×10^{-2}	1.31×10^{-1}	x	9.29×10^{-3}	-9.09×10^{-3}	2.40×10^{-2}	1.83×10^{-2}	x	4.81×10^{-3}	-1.98×10^{-3}	species.year
Substances causing acidification of terrestrial ecosystems	1.08×10^{-1}	3.26×10^{-1}	x	2.86×10^{-2}	-2.63×10^{-2}	7.14×10^{-2}	4.56×10^{-2}	x	1.43×10^{-2}	-5.67×10^{-3}	species.year
Substances causing eutrophication of freshwater ecosystems	4.94×10^{-2}	1.83×10^{-1}	x	1.31×10^{-2}	-1.76×10^{-2}	3.54×10^{-2}	2.57×10^{-2}	x	7.09×10^{-3}	-3.42×10^{-3}	species.year
Substances causing eutrophication of marine ecosystems	3.12×10^{-5}	4.58×10^{-5}	x	8.25×10^{-6}	-1.25×10^{-5}	3.11×10^{-5}	6.42×10^{-6}	x	6.22×10^{-6}	-3.21×10^{-6}	species.year
Ecotoxic substances affecting terrestrial ecosystems	1.24×10^{-2}	6.45×10^{-2}	x	3.29×10^{-3}	-3.94×10^{-3}	7.61×10^{-3}	9.02×10^{-3}	x	1.52×10^{-3}	-6.91×10^{-4}	species.year
Ecotoxic substances affecting freshwater ecosystems	1.23×10^{-2}	5.68×10^{-2}	x	3.25×10^{-3}	-4.48×10^{-3}	8.03×10^{-3}	7.95×10^{-3}	x	1.61×10^{-3}	-8.12×10^{-4}	species.year
Ecotoxic substances affecting marine ecosystems	2.48×10^{-3}	1.11×10^{-2}	x	6.56×10^{-4}	-8.96×10^{-4}	1.62×10^{-3}	1.56×10^{-3}	x	3.23×10^{-4}	-1.63×10^{-4}	species.year
Carcinogenic toxic substances affecting human health	1.10×10^{2}	3.93×10^{2}	x	2.90×10^{1}	-2.99×10^{1}	5.44×10^{1}	5.50×10^{1}	x	1.09×10^{1}	-4.39×10^{0}	DALY

Table 3. Cont.

Non-carcinogenic toxic substances that affect human health	8.97×10^{1}	2.89×10^{2}	x	2.38×10^{1}	-3.22×10^{1}	5.87×10^{1}	4.04×10^{1}	x	1.17×10^{1}	-5.88×10^{0}	DALY
Land use processes	2.39×10^{-2}	5.50×10^{-1}	x	6.32×10^{-3}	-6.98×10^{-3}	1.49×10^{-2}	7.69×10^{-2}	x	2.99×10^{-3}	-1.29×10^{-3}	species.year
Mineral resource depletion processes	7.49×10^{5}	1.46×10^{6}	x	1.98×10^{5}	-1.60×10^{5}	4.03×10^{5}	2.05×10^{5}	x	8.06×10^{4}	-2.83×10^{4}	USD
Processes that deplete fossil fuel resources	7.88×10^{6}	1.50×10^{7}	x	2.09×10^{6}	-1.88×10^{6}	7.28×10^{6}	2.10×10^{6}	x	1.46×10^{6}	-6.05×10^{5}	USD
Processes that affect water availability, affecting human health	4.29×10^{2}	5.23×10^{0}	x	1.14×10^{2}	-5.93×10^{2}	1.56×10^{2}	7.33×10^{-1}	x	3.12×10^{1}	-6.31×10^{1}	DALY
Processes that affect water availability, affecting terrestrial ecosystems	2.61×10^{0}	4.43×10^{-1}	x	6.91×10^{-1}	-3.61×10^{0}	9.50×10^{-1}	6.21×10^{-2}	x	1.90×10^{-1}	-3.84×10^{-1}	species.year
Processes that affect water availability, affecting aquatic ecosystems	1.17×10^{-4}	5.35×10^{-6}	x	3.10×10^{-5}	-1.61×10^{-4}	4.27×10^{-5}	7.49×10^{-7}	x	8.55×10^{-6}	-1.71×10^{-5}	species.year

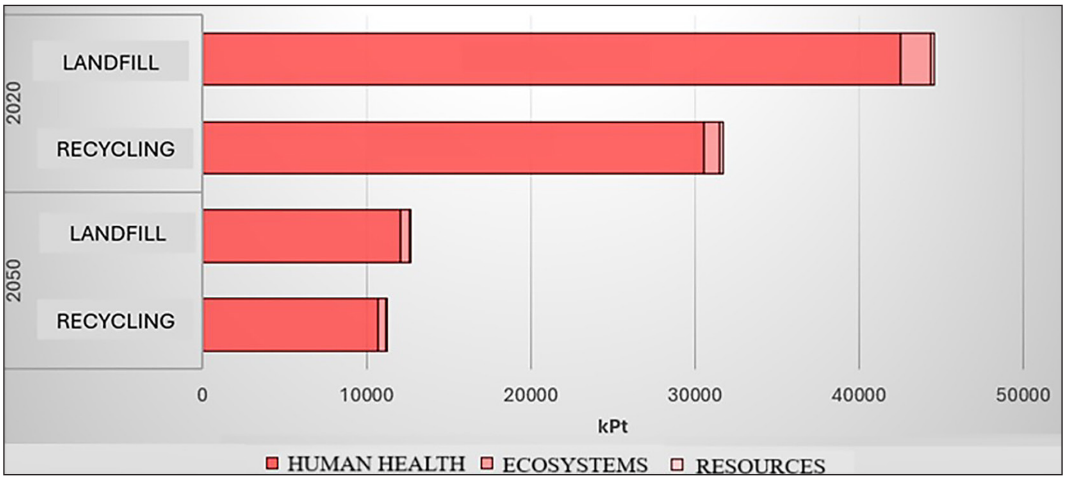

Figure 4. Grouping and weighing environmental impacts in the life cycle of fuel cell electric buses (FCEV) for the analysed impact areas, considering different post-consumer management methods (ReCiPe 2016 model, unit: kPt – thousands of environmental points)

the environmental impact remains high and can offset the benefits of zero emissions during operation. In turn, the use of hydrogen produced using renewable energy sources allows for a significant reduction in climate impacts. The greatest challenge in the context of FCEV development remains the high energy intensity of the hydrogen production processes. Although hydrogen does not generate carbon dioxide emissions during end use, its environmental impact depends on the production technology and the source of the energy used. Therefore, it is crucial to confirm the origin of hydrogen to classify it as a clean energy source. For this purpose, a novel model – the hydrogen purity index – was developed, which provides the basis for further research and development in this area (24–26).

CONCLUSIONS

The analysis comparing the harmfulness of two types of buses currently in use and with the forecasts for 2050 showed that:

1. Recycling of plastics, materials, components and working assemblies at the end of their

service life would enable a significant reduction of hazardous impacts over the entire life cycle of all the vehicles tested.
2. The highest values of total destructive impacts for the studied variants were recorded for the life cycles of buses with internal combustion ICEV-D, both those in operation now and in 2050, and the TTW stage was the main source (approx. 43%) of undesirable consequences for the environment.
3. Replacing the currently most commonly used “grey” or “black” hydrogen with hydrogen from more sustainable sources – “blue” or “green” – in FCEVs would contribute to further reducing their negative environmental impact, reaching levels significantly lower than those observed for the ICEV-D vehicles.
4. Among the types of drive systems of the analysed vehicles, the highest environmental impact was recorded in the case of the solutions based on diesel fuel.
5. Of all the impact categories assessed, the most harmful to the environment were the emissions causing the formation of suspended particulate matter (PM), emissions of non-carcinogenic toxic substances, factors intensifying global warming and processes limiting access to water resources – all of which have a negative impact on human health.
6. The implementation of recycling as a form of vehicle management after the end of use can significantly reduce their harmful impact on human health. For the vehicles powered by conventional fuels, this mainly concerns the reduction of particulate matter (PM) emissions and non-carcinogenic toxic substances, while in the case of electric buses – limiting the impacts related to the use of water resources.

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