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Environmental life cycle assessment of alternative fuels for city buses: A case study in Oujda city, Morocco

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HIGHLIGHTS

- Alternative fuels are identified for sustainable development.
- The environmental life cycle assessment of various alternative buses is performed.
- The impacts of selected alternative buses on human health and ecosystem quality are determined.
- The electric and fuel cell buses have performed as the best options for sustainable public transportation.

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ABSTRACT

The road transport sector, particularly public transport, generates significant greenhouse gas emissions due to the excessive use of petroleum-based fuels. The use of alternative fuels with lower environmental impacts is therefore a major challenge to move towards a more sustainable public transport sector. In this context, the current study presents an environmental life cycle assessment of alternative buses, including hybrid (diesel-electricity), electric, and fuel cell buses at a city level in Oujda, Morocco. This study is perfromed according to three main outputs: total energy use by fuel type, GHG emissions, and criteria air pollutants. It is concluded that electric and fuel cell buses represent efficient and sustainable alternatives to public transport during the operational phase and their deployment in Oujda city can potentially offer significant environmental savings in terms of GHG emissions and air pollutants during both the WTT and TTW phases.

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Nomenclature

CH_4	Methane
CIDI	Compression Ignition Direct injection
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
EI99	Eco-indicator 99
GHG	Greenhouse Gas
GREET	Greenhouse gases, regulated emissions, and energy use in transportation
ISO	International Organization for Standardization
LCA	Life cycle assessment
LNG	Liquefied natural gas
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
PM_{10}	Particulate matter 10
$PM_{2.5}$	Particulate matter 2.5
Pt	Point
SO_x	Sulfur oxide
SI	Spark Ignition
TJ	Terajoule
TTW	Tank to wheel
VOC	Volatile organic compound
WTT	Well to tank
WTW	Well to wheel

Introduction

Public transport buses: an overview

Worldwide, the transport sector consumed approximately 31,310 TWh of final energy in 2015 and was responsible for nearly 14% of GHG emissions [1].

Particularly, public transport is a major contributor to transport energy consumption worldwide [2]. It is clear that public transport used in many cities is known to be more efficient than private vehicles in terms of passenger capacity and environmental impact [3]. However, the use of petroleum-based fuels to drive city buses is causing considerable GHG and air pollutant emissions [4].

Public transport plays a key role in a city's mobility and accessibility and reduces traffic congestion and other traffic externalities; at the same time, it is also the main source of hazardous air pollutants affecting urban areas that can have adverse effects on human health, including respiratory problems [5].

As highlighted by Agarwal and Singh [6], public transport in cities faces great challenges. These challenges include the need to address environmental problems (air pollution, noise, and traffic congestion) and operational problems (extreme overcrowding due to the inadequate system, inaccessibility and inefficient bus lines, poor stop locations, and a general increase in operating costs). Therefore, the adoption of clean fuels and innovative propulsion systems for public transport is undoubtedly the most promising option for reducing health and environmental problems linked to the public transport sector [7].

Overall, the transition to low-carbon public transport is a major challenge worldwide. Therefore, cities have an important role in helping to reduce CO_2 emissions worldwide by implementing a transition to more sustainable transport options [5,8].

A brief insight into alternative fuels

The improvement of the efficiency and sustainability of public transport depends largely on a number of key factors including the development of green energy, innovative infrastructure, and institutional framework [9]. There is, then, an important opportunity for public transport to benefit from the development of the market for alternative technologies because urban bus transport is characterized by fixed routes, centralized depots, and shared infrastructure that allows for the offering of quality services, to contribute to the successful implementation of innovative mobility [10]. For each urban area, different parameters like costs, energy source (fuel), and driving conditions are taken into account when choosing an appropriate propulsion system [11].

Many alternative fuels for city buses are widely available in the market, including CNG, LNG, hybrid (diesel-electricity), electricity, and hydrogen [7]. Natural gas – which contains mainly methane - is considered a promising fuel and many cities are looking to utilize it within public transport [12]. In fact, natural gas emits fewer air pollutants and produces approximately 25% less CO_2 per unit of energy than diesel fuel [13,14].

Compressed natural gas is natural gas, compressed under very high pressure, typically 3,000 to 3,600 psi [15]. Compared to diesel buses, the CNG buses generate fewer emissions, including particulate matter (PM) and NO_x. Additionally, in terms of GHGs and especially CO_2, CNG buses generally emit lower levels of CO_2 per traveled distance than conventional diesel buses. For these reasons, it can be noted that a significant trend towards the replacement of diesel buses with CNG buses can be remarked in recent years [16,17].

The use of liquefied natural gas (LNG) in the transport sector has increased significantly in many regions of the world. The production process for LNG involves cooling natural gas to −162 °C [18]. It is used as a clean alternative fuel mainly for heavy vehicles such as city buses and large trucks [19,20]. So, LNG is ideally suited for the direct replacement of diesel for heavy-duty vehicles, but it can be considered for long-distance use.

The hybrid buses represent an alternative to conventional diesel buses in public transport. These buses generally have a propulsion system, operating in series or parallel, with a combustion engine and a traction battery [21]. Further, the use of hybrid technology requires a regenerative braking system, which converts kinetic energy into electrical energy giving the possibility to save a considerable amount of fuel [22]. The main advantage of hybrid technology is that it does not require the implementation of new infrastructure [7,23].

Some researchers outlined that the use of an electric bus is better than the use of a diesel bus from a long-term perspective [8]. In fact, the electric bus offers many advantages, including lower emissions with less noise compared to conventional diesel buses. It also provides a regenerative braking system, which converts the kinetic energy released during braking into electrical energy that can recharge the battery [10,24]. Under some conditions, electric buses can be more cost-effective than diesel buses due to lower operating and maintenance costs and higher efficiency [21]. However, the central problem with electric buses concerns the batteries because their capacity does not provide sufficient autonomy for covering longer trips [25].

Fuel-cell buses are powered by hydrogen, which is ideally suitable especially in urban areas known for their hydrogen production. Presently, many areas in the world, including Europe, are involved in experiments and other research into fuel-cell buses [7,26]. One of the foremost advantages of using fuel-cell buses is their low exhaust emissions, but they face significant challenges, including their high cost, which results from the significant expenses associated with hydrogen production [26,27].

Methodology

An overview of LCA-based studies applied in the public transport sector

Researchers worldwide have increasingly begun focusing on the environmental impacts linked to feedstock production, fuel refining, and vehicle operation, based on life cycle assessments.

Various examinations have been conducted to evaluate the environmental impacts of alternative fuels in public transport using the LCA framework.

According to Bicer and Dincer [28], a comparative analysis of the environmental impacts of alternative and conventional fuel vehicles was conducted using a "well-to-wheel" approach based on a life cycle assessment in terms of seven different categories of environmental impact (abiotic depletion, acidification, eutrophication, global warming, human toxicity, ozone depletion, and terrestrial ecotoxicity). In the conducted study, they found that electric and plug-in hybrid vehicles have higher values of human toxicity, terrestrial ecotoxicity, and acidification, in particular during the manufacturing and maintenance stages. Nevertheless, hydrogen vehicles represent an alternative option with environmental benefits, due to their higher energy densities and better fuel economies during vehicle operation.

The comparative analysis of public transport alternatives based in the Lithuanian city of Kaunas was presented by Kliucininkas et al. [29]. The LCA of fuel production systems for urban buses and trolleybuses was presented. A result of the comparative analysis highlighted that biogas and electrically powered trolleybuses are likely the best alternatives for the modernization of public transport in Kaunas.

According to McKenzie et al. [30], a life cycle assessment was performed to estimate urban bus costs and GHG emissions using a hybrid input-output model. The objective was to compare ultra-low-sulfur diesel with a diesel-electric hybrid, compressed natural gas, and hydrogen fuel cells. The cost of emission reductions over their life cycle and their sensitivity to fuel price fluctuations, passenger demand, and technological characteristics that affect performance and emissions, were taken into account.

A comparative analysis of the lifecycle environmental impacts of conventional diesel buses with battery-electric buses was presented by Cooney et al. [31]. From the analysis, it was shown that the electric bus was preferred in only eight states, including Washington and Oregon. In fact, the increased development of batteries limits the impacts on the life cycle of the electric bus.

Ercan and Tatari [32] presented in detail the total emissions of air pollutants and their impacts on the environment over the lifetime of an urban bus with different fuel alternatives using an input-output (IO) -based hybrid LCA model. It was revealed that the battery-powered electric transit bus emits significantly less CO_2 than diesel and other alternative fuels, but that the hybrid bus has the same emissions-producing operating cycles as the battery-powered electric transit bus.

Jwa and Lim [33] introduced a life cycle assessment using GREET 2016 software for lithium-ion battery-electric buses and diesel buses to evaluate all environmental impacts. The energy consumption and emissions of the electric bus were analyzed and compared to the diesel bus. The principal finding was that electric buses were preferable compared to diesel buses from both energy and environmental points of view.

The environmental benefits of alternative fuels for city buses, including LNG buses, liquefied petroleum gas buses, and hydrogen fuel-cell buses, were compared to diesel buses in Ref. [34]. An assessment of the carbon footprint of the life cycle for these buses was investigated, to aid the decision-makers at the government level in making the appropriate choices. The results showed that the use of hydrogen fuel-cell buses as an alternative to diesel buses reduces carbon emissions by 47%.

System description

The current study focuses on the fuel life cycle or well-to-wheels process, which includes the following three stages: feedstock production, fuel refining, and bus operations. These stages can be further grouped into two main phases: the well-to-tank phase is known as the WTT phase, which encompasses various processes, including feedstock production, which includes all operations from the well to the feedstock production site. It also involves the transportation of the feedstock (petroleum, coal, natural gas, renewable energy) to the fuel production site and includes the activities performed between the feedstock supply and the fuel production site, which includes the activities performed along the route towards the fuel production site. The second phase is related to fuel delivery, which covers all activities between the fuel production site and the bus tank, which is referred to as TTW (tank-to-wheel), referring to the operation of the bus throughout its lifetime [35–37].

The objective of the paper

This paper examines the environmental impacts of the different propulsion systems for public transport buses in terms of the fuel life cycle. For this purpose, an in-depth analysis was conducted based on the LCA approach, as a way to evaluate the relevant environmental impacts regarding the following elements: total energy use by fuel type, GHG emissions, and criteria air pollutants. Some of the options analyzed are hybrid, electric, and fuel-cell buses, as an alternative to diesel buses. An important feature of this study is that the results obtained through the LCA approach are extrapolated to the city level by considering a practical case study that takes into account the real conditions of urban bus operation in the Moroccan city of Oujda.

The basic structure of the methodology

A Lifecycle assessment is used as a research method to evaluate and quantify the environmental effects of different fuel options used in city buses. This assessment takes into account the whole fuel lifecycle, from the material extraction, processing, and fuel production phase, to the vehicle operation phase. The LCA conducted in this study was based on the ISO 14040–14043 standards. It is structured as follows: definition of goals and scope, inventory analysis, impact assessment, and interpretation (see Fig. 1) [38–40].

The goal and scope definition

This paper discusses the environmental impacts of the different powertrains of city buses in terms of their fuel cycles. For this purpose, an extensive analysis based on the LCA framework was conducted to examine the environmental impacts using the following criteria: total energy use by fuel type, GHG emissions, and criteria air pollutants (SO_x, CO, NO_x, PM_{10}, $PM_{2.5}$, and non-methane volatile organic compounds [often referred to as VOCs]).

In addition, an assessment of these environmental impacts generated by the use of alternative fuels, such as diesel-electric hybrid, electricity, and hydrogen at the city level was performed, taking into account the real operating conditions gathered from the current operator of public transport buses, MOBILYS, in Oujda city (Morocco).

Inventory data sources

Several sources were used to obtain the primary life cycle inventory (LCI) compiled in this study. These include the following: (1) the Ecoinvent database version 3.3 published by the Ecoinvent Centre throughout OPENLCA software as

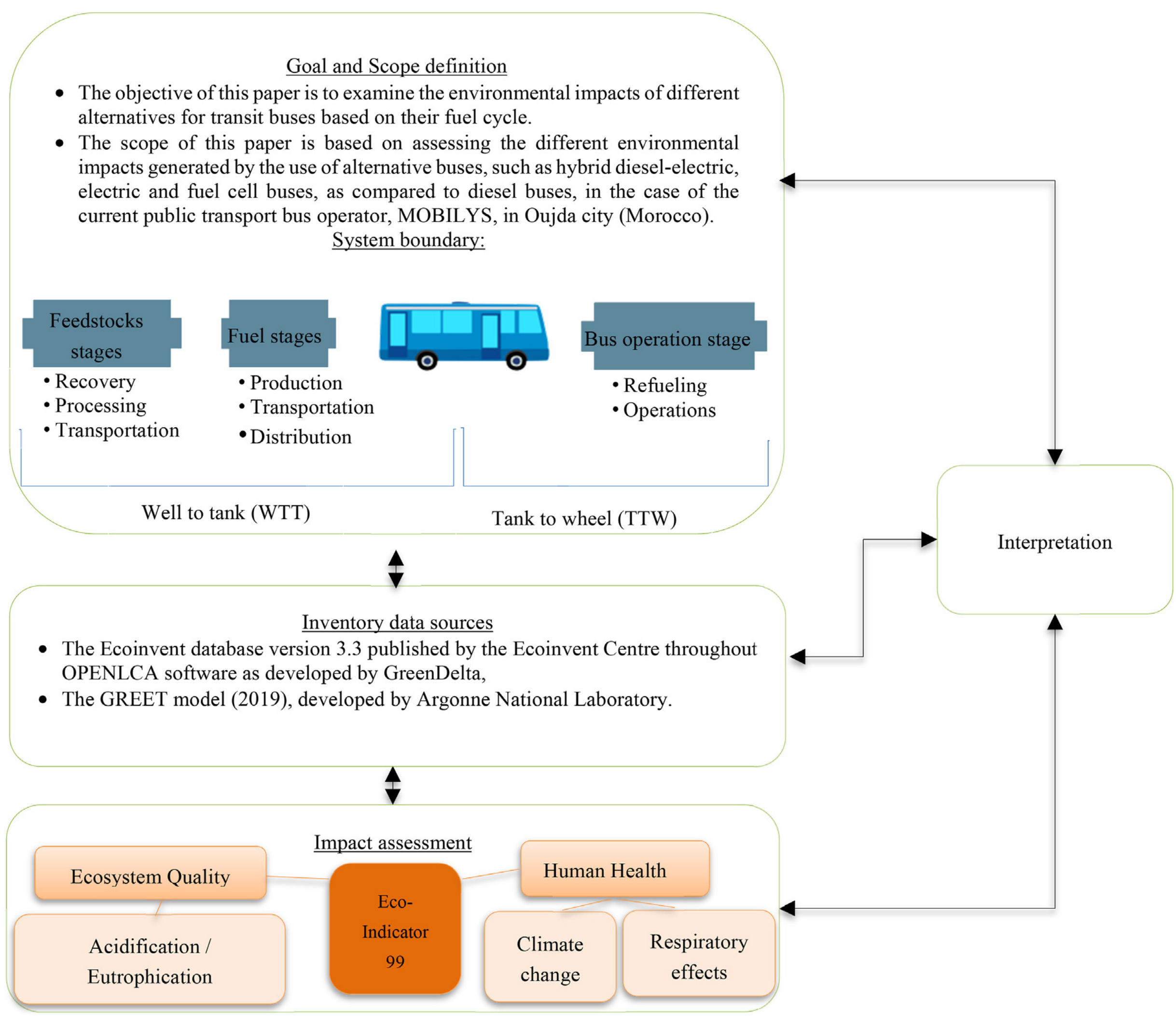

Fig. 1 – A life cycle assessment framework.

developed by GreenDelta, and (2) the GREET model (2019), developed by Argonne National Laboratory.

Impact assessment

The current study was based on the Eco-indicator 99, which is characterized by providing the estimations of the environmental impact from different databases, taking into account different perspectives (individualistic, egalitarian, and hierarchical) [41]. The individualistic perspective makes decisions based on a short-term view and focuses mainly on observed causality. The egalitarian perspective takes into account the principle of prevention, where decisions are made from a long-term perspective. From the other side, the hierarchical perspective considers factors supported by scientific and political authorities that have an adequate level of scientific recognition [42]. The three groups of environmental damages that represent the Eco-indicator 99 are outlined as follows [43] (see Fig. 2):

- Damage to human health, such as substances that cause climate change, ozone depletion, carcinogenic effects, respiratory effects, and ionization;
- Damage to ecosystem quality, which includes acidification, ecotoxicity, eutrophication, and land use;
- Damage to resources that includes the use of primary resources and fuels.

For the present study, there was applied the Eco-indicator 99, based on an egalitarian (E) perspective, and aimed to address mainly human health and ecosystem quality. Therefore, OPENLCA, a software developed by GreenDelta, was used to perform the environmental impact assessment, coupled with the Ecoinvent database version 3.3.

Application of the methodology

Description of the case

The public transport in Morocco represents a key concern from both socio-economic and environmental perspectives because it contributes significantly to the development of the population's mobility and quality of life [44].

Oujda is a city located in the northeast of Morocco, about 15 km west of the Algerian border and 55 km south of the Mediterranean coast. This city is the capital of the eastern region in northeastern Morocco with a population of approximately 500,000 inhabitants as of 2014 [45].

The most-used mode of transportation in Oujda city is walking, comprising a percentage of 54%, followed by public transport with a share of 21% (14% by bus and 7% by taxi), and private car accounting for 17% of the total mobility. With regard to two-wheeled mobility, only 5% of the total mobility uses two wheels (see Fig. 3) [46].

The public transport company, MOBILYS, has become the exclusive operator of public transport by bus in Oujda city. The company operates a total bus fleet of 81 standard buses (see

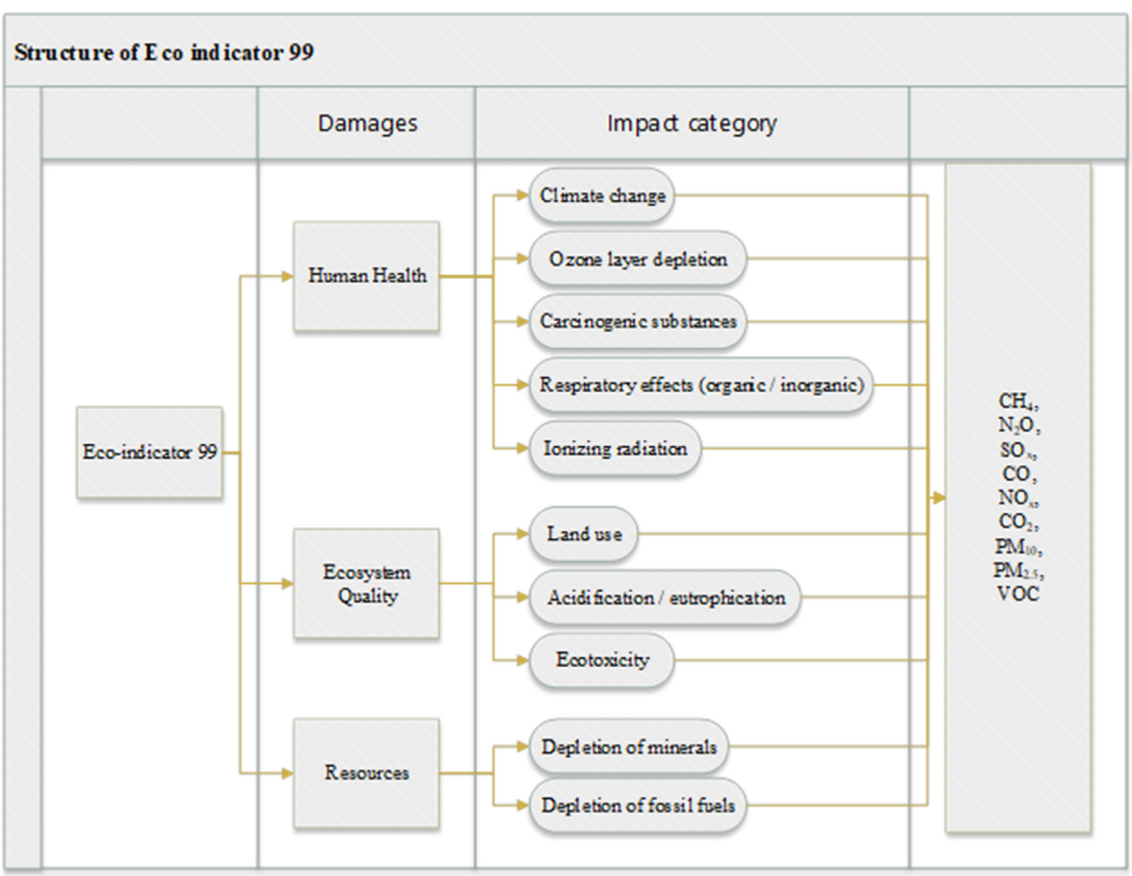

Fig. 2 – Structure of Eco indicator 99.

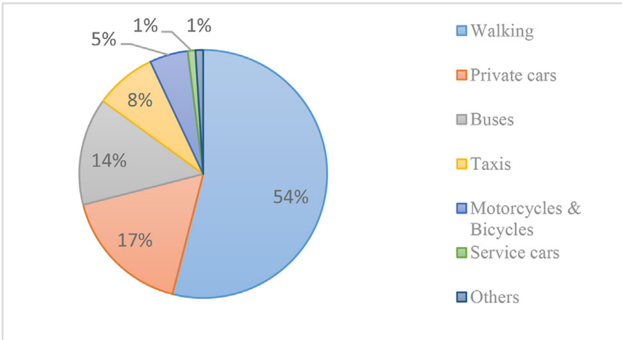

Fig. 3 – Mobility distribution in Oujda city by mode.

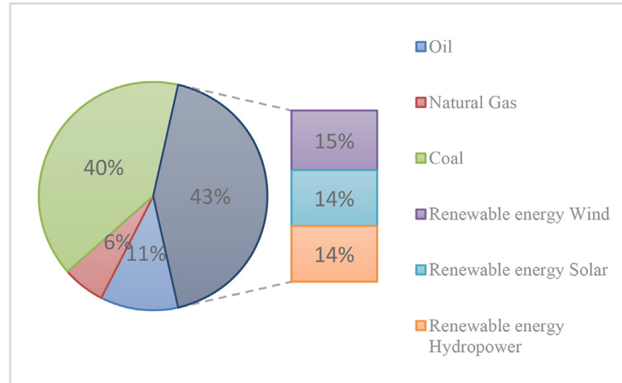

Fig. 4 – Moroccan power generation mix (2019).

Table 2). It covers a network of 341 km, which includes 21 urban lines [46].

To govern public transport by bus in Oujda city, delegated management was chosen to act as a form of public-private partnership based on a contractual agreement between a public authority (the urban municipality) and a private company [47].

The urban buses in Oujda city are comprised of Euro 5 engines, electronic systems, surveillance cameras to improve passenger safety, intelligent transport systems equipped with GPS and Wi-Fi networks, as well as a means of access for people with reduced mobility [46].

Assumptions and input data

Alternative fuels selected for buses are subject to an environmental assessment using the GREET model (2019), to evaluate total energy consumption, GHGs, and criteria air pollutants, based on a WTW analysis [14].

Different assumptions are considered to conduct this study:

- The daily hours of operation are 14 h, but the effective hours of operation used is only 11.2 h, representing 80% of the operational rate, because of bus stops and traffic.
- Only standard buses are taken into account and they have some specifications (see Table 1).
- The electric buses are powered by the Moroccan power generation mix, detailed as follows (see Fig. 4).

Table 1 – Technical specifications of the studied buses [48].

	Standard Bus
Model	VOLVO B7R LE
Length (m)	12
Width (m)	2.55
Height (m)	3.18
Permitted gross vehicle weight (kg)	19,000
Fuel used	Diesel
Power of engine types	Euro 5
Fuel consumption (l/100 km)	38
Seat capacity	38 + 1(driver)

- The bus fleet of the city of Oujda covers an average of 5,394,043 km per year, based on Table 2.
- The weighting of the different air pollutant emissions is presented in the form of a point score, where one point (Pt) represents the annual environmental load. For example, the amount of CO_2 represents a value of 0.0040645 Pt per kg for climate change (see Table 3).

Analysis and discussions of the results: WTW analysis for each bus technology at a city level

Total energy use

The total energy use of alternative fuels considers both non-renewable and renewable energy. The main sources of non-renewable energy are coal, natural gas, and oil. These energy sources can lead to increased emissions of air pollutants. In contrast, the main sources of renewable energy are solar, wind, and hydropower can be seen from the Moroccan energy mix (see Fig. 4).

In the first subsection, energy utilization for each bus technology is presented in Fig. 5. Results are given on an annual basis and correspond to the case of Oujda city based on the field data presented earlier. As can be seen, the oil consumption for hybrid buses during the WTT phase is 28% lower than that of diesel buses as a reference case. Likewise, fuel cell buses typically consume 0.52 TJ of oil, a savings of 90% of their oil consumption compared to diesel buses (5.34 TJ). Similarly, in the TTW phase, the oil consumption of hybrid buses is lower than that of diesel buses, approximately 80 TJ against 112 TJ, which results in a reduction of 28%. It is also clearly seen that fuel cell buses are operated with no oil consumption. In turn, electric buses use a higher amount of oil, which represents a reduction of 95% of their oil consumption compared to diesel buses (112 TJ).

On the other hand, electric buses are characterized by a significant proportion of coal in the WTT and TTW phases. This finding is reasonable keeping in mind the energy mix of the country that includes increased shares of coal and renewable energy.

In terms of natural gas consumption, the electric and hybrid buses in the WTT phase conduct to low consumption of natural gas compared to diesel buses, at 3.44 TJ and 9.61 TJ respectively. However, fuel cell buses are significantly more

Table 2 – An overview of the lines with their specific operation [46].

Lines	Distance (km)	Bus fleet	Number of trips	Distance round trip in km
1	7.5	5	26	15
2	8.9	3	30	17.8
3	6.1	4	29	12.2
4	6.5	3	35	13
5	4.1	3	31	8.2
7	4.7	1	30	9.4
8	4.4	3	32	8.8
9	9.3	4	23	18.6
11	9.5	2	25	19
13	6.5	1	25	13
14	6	6	27	12
15	7.1	6	27	14.2
16	6.55	3	28	13.1
17	6.7	4	29	13.4
18	4.35	3	38	8.7
19	4.5	4	39	9
20	11.95	6	14	23.9
21	6.15	5	26	12.3
23	5	2	31	10
24	13.3	5	15	26.6
25	11.8	8	15	23.6

Table 3 – Weighting of the different air pollutant emissions.

	Eco-indicator 99, (Egalitarian)		
	Ecosystem Quality	Human Health	
	Acidification/Eutrophication	Climate Change	Respiratory Effects
CO_2 (Pt/kg)		0.0040645	
CH_4(Pt/kg)		0.085161	0.00024774
N_2O (Pt/kg)		1.3355	
VOC (Pt/kg)			0.024774
CO (Pt/kg)		0.0062323	0.014148
NO_x (Pt/kg)	0.55682		1.7245
PM_{10} (Pt/kg)			7.2581
$PM_{2.5}$ (Pt/kg)			13.548
SO_x (Pt/kg)	0.10146		1.0568

intensive with respect to the use of natural gas during the WTT and TTW phases.

Regarding renewable energy usage, the electric and fuel cell buses in the WTT phase consume a considerable amount relative to the other options, accounting for 8 TJ and 3.15 TJ, respectively. In the operation phase of electric buses, a remarkable level of renewable energy use can be highlighted when compared to the other bus alternatives.

GHG emission

The GREET model assesses greenhouse gas (GHG) emissions over the fuel life cycle (well-to-wheel), including CO_2, CH_4, and N_2O for different bus alternatives. Table 4 shows the GHG emissions for the investigated case. During the WTT phase, it can be seen that hybrid buses emit less GHG than the other alternatives, while fuel cell buses and electric buses produce significantly higher values. The reason for this is, on the one hand, the production of hydrogen gas is based on the steam methane reforming (SMR) process, which uses fossil natural gas and in particular methane (CH_4) as the main feedstock. The SMR process requires high energy consumption to reach the high temperature required for its reforming process, which results in large amounts of CO_2 emissions. Similarly, the production of batteries relies in particular on the use of electricity from an energy mix with an increased share of coal. During the TTW phase, it is possible to see that the electric and fuel cell buses operate sustainably and no emit any GHG emissions. Oppositely, hybrid buses, due to the partial operation using diesel fuel, emit a considerable amount of GHG but their emission level remains 28% lower than the reference case.

Criteria air pollutant emissions

The criteria air pollutants in urban areas that have an impact on public transportation include NO_x, SO_x, CO, VOC, PM_{10}, and $PM_{2.5}$. These air pollutants contribute to the formation of smog in the atmosphere, which leads to various health problems such as respiratory diseases, cardiovascular diseases, etc [49].

Fig. 6 shows the air pollutants related to a well-to-wheel analysis of each bus technology investigated in the case study:

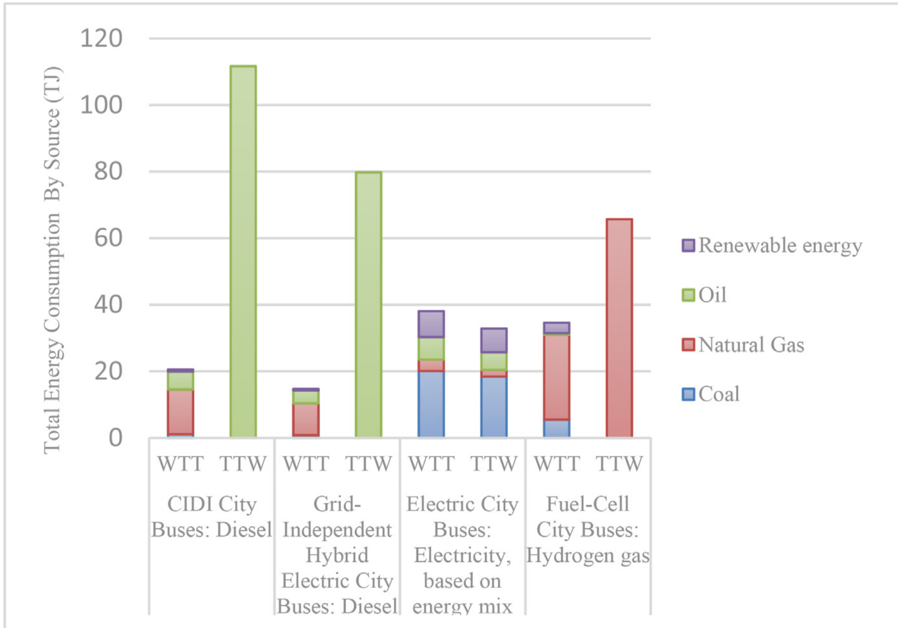

Fig. 5 – Total energy consumption by fuel type in the case of MOBILYS.

Table 4 – GHG emissions in the case of MOBILYS.

	CIDI City Buses: Diesel		Grid-Independent Hybrid Electric City Buses: Diesel		Electric City Buses: Electricity, based on the energy mix		Fuel-Cell City Buses: Hydrogen gas	
	WTT	TTW	WTT	TTW	WTT	TTW	WTT	TTW
GHG emissions ($T\ CO_{2\ eq}$)	1715	8377	1225	5986	5174	0	6012	0

- NO_x, CH_4, SO_x, and CO emissions

During the WTT phase, it can be seen that electric buses emit a large quantity of SO_x emissions due to their battery manufacturing, while hybrid buses release significantly lower amounts of SO_x emissions than other alternative buses, achieving a savings of 28% compared to diesel buses. Similarly, hybrid and fuel cell buses cause slightly reduced NO_x emissions, with an economy of 28% and 12% compared to diesel buses, respectively. One can also remark that these emissions are relatively high for electric buses with approximately 6.55×10^3 kg annually for the city level. In terms of CO emissions, it can be seen that electric and hybrid buses are characterized by lower CO emission levels compared to diesel buses. Their utilization can lead to savings of around 42% and 28%, respectively. Oppositely, fuel cell buses have a significantly higher level of CO emissions, at 1.39×10^3 kg, which is comparable to a certain extent to the diesel bus emissions. Furthermore, electric, hybrid, and fuel cell buses have the potential to mitigate VOC emissions than diesel buses, by about 46%, 28%, and 7%, respectively.

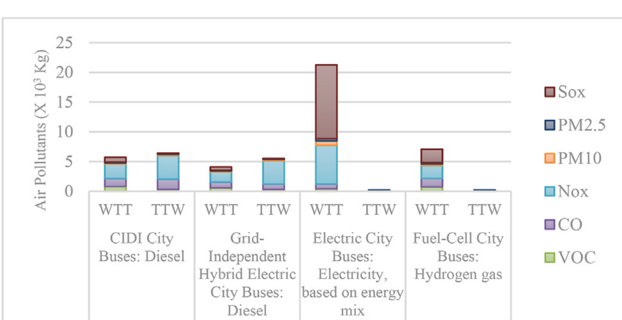

Fig. 6 – Criteria air pollutants for each technology bus in the case of MOBILYS.

Looking at the results corresponding to the TTW phase, it is possible to highlight the absence of NO_x, SO_x, CO, and VOCs for both electric and fuel cell buses. Similarly, it can be seen that hybrid buses emit higher amounts of NO_x and VOC emissions than other alternatives and are very close to the reference case (diesel buses). However, hybrid buses achieve a significant impact with respect to diesel buses, with a savings of 28% in SO_x emissions and 50% in CO emissions.

- PM_{10} and $PM_{2.5}$ emissions

In the WTT phase, it can be seen that electric and fuel cell buses generate higher amounts of PM_{10} and $PM_{2.5}$ emissions than the other alternatives. In contrast, hybrid buses are significantly less intensive in PM_{10} and $PM_{2.5}$ emissions, with a significant reduction of 28%, relative to diesel buses.

During the bus operation, electric and fuel cell buses generate relatively small amounts, approximately 0.162×10^3 kg of PM_{10} emissions and 0.042×10^3 kg of $PM_{2.5}$ emissions. However, compared to diesel buses, hybrid buses produce practically the same amounts in terms of PM_{10} and $PM_{2.5}$ emissions, estimated at 0.24×10^3 kg of PM_{10} emissions and 0.113×10^3 kg of $PM_{2.5}$ emissions.

Impact assessment of air pollutants at a city level

The objective of this subsection is to carry out an environmental impact assessment of each bus technology for the investigated case study. Using the Eco-Indicator 99 methodology, two categories of damage are considered: human health (climate change and respiratory effects) and ecosystem quality (acidification and Eutrophication). For this purpose, the results obtained from the well-to-wheel analysis mentioned in the previous subsections are considered and converted into points (Pt) using the OPENLCA software developed by GreenDelta, based on the egalitarian perspective given by the Eco-Indicator 99 [4,28].

Fig. 7 presents the environmental impact assessment from the following impacts: climate change, respiratory effects, and acidification/eutrophication. It can be seen that electric and fuel cell buses contribute strongly to the decrease of climate change impacts compared to other alternatives, as they present the lowest score in terms of CO_2 with a value of 20×10^3 Pt for electric buses and 23×10^3 Pt for fuel cell buses. It can also be seen that hybrid buses are characterized by potentially lower impacts in terms of respiratory effects than the other options because their scores are lower in terms of SO_x, $PM_{10,}$ and $PM_{2.5}$ emissions. The scores are, however, significantly higher for electric buses for this criterion. A lower impact on respiratory effects for fuel cell buses was predicted compared to diesel buses, because of their lower scores for NO_x emissions. On the other hand, from an acidification and eutrophication point of view, fuel cell buses are rated as an alternative option with a significantly lower impact than diesel buses in terms of NO_x emissions, with a score of 1.2×10^3 Pt, thus significantly reducing the related adverse effects compared to electric buses.

Sensitivity analysis

A sensitivity analysis was conducted to examine the impact of the national electricity mix on energy use, GHG emissions, and criteria air pollutants of electric buses. It was assumed that the national electricity mix is based on coal, natural gas, oil, and renewable energy (solar, wind, and hydropower).

Fig. 8 shows the results of the investigated sensitivity analysis, which considered the fuel life cycle (well-to-wheel). Various scenarios of power generation modes ranging from heavily dependent on fossil fuels to a more sustainable energy mix were studied (see Table 5). The scenarios were established based on the targets fixed by the Moroccan energy policy for a realistic analysis. It can be seen that electric buses during the WTT phase consume, under scenario 1, about 37% of coal, 15% of natural gas, 33% of oil, and 15% of renewable energy, while, under scenario 3, they consume 31% of coal, 34% of natural gas, 7% of oil, and 28% of renewable energy, which would reduce up to 16% of coal, 78% of oil, along with increased usage of natural gas and renewable energy. On the other hand, operating an electric bus leads to the use of 41% for coal, 10% for natural gas, 33% for oil, and 16% for renewable energy under scenario 1. Under scenario 3, electric buses consume about 34% of coal, 31% of natural gas, 5% of oil, and 30% of renewable energy, which results in a reduction in terms of coal and oil along with an increase in renewable energy and natural gas contribution. It can also be noted that the electric buses emit during the WTT phase, under scenario 1, about 5,773 t $CO_{2\ eq}$, while they reach about 3,290 t $CO_{2\ eq}$ under scenario 3, which leads to a reduction of 43% in GHG emissions. Thus, the potential contribution to the electricity mix is significant and will have a major impact on the level of energy consumption and GHG emissions during the WTT and TTW phases.

Looking at the results corresponding to the evolution of NO_x, SO_x, CO, VOC, $PM_{10,}$ and $PM_{2.5}$ emissions in the three scenarios, it can be seen that the electric buses were significantly improved in terms of NO_x, SO_x, VOC, $PM_{10,}$ and $PM_{2.5}$ emissions during the WTT phase, when switching from scenario 1 to 3, but a minor increase in terms of CO emissions.

Obviously, the implementation of renewable energy support policies will generally become important to promote and prioritize their use.

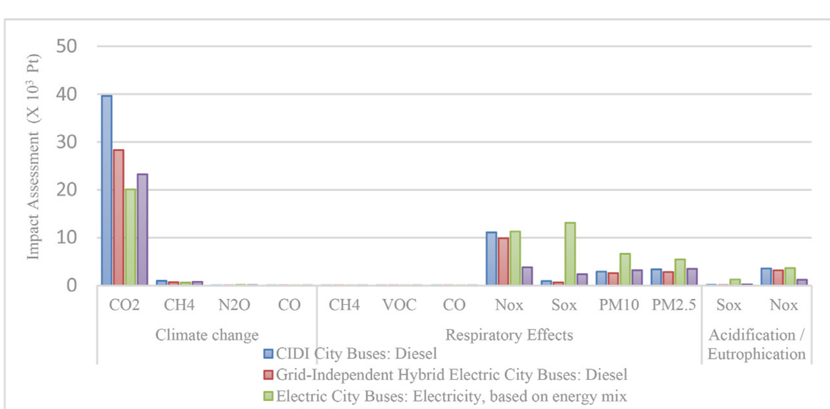

Fig. 7 – Environmental impact assessment for each bus technology in the investigated case.

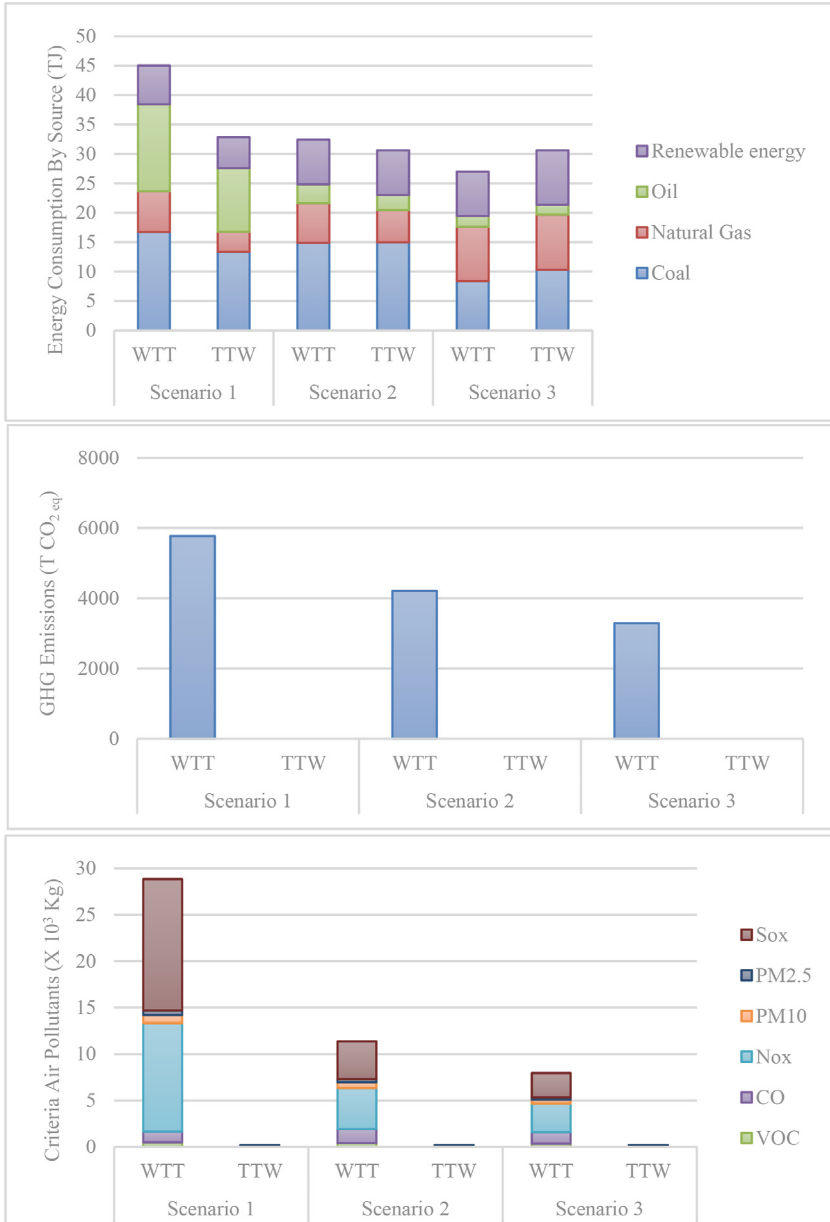

Fig. 8 – WTW-based sensitivity analysis of energy use, GHG emissions and criteria air pollutants of electric buses under three scenarios.

Table 5 – Scenarios for the national electricity mix.

	Oil	Natural Gas	Coal	Renewable Energy		
				Wind	Solar	Hydropower
Scenario 1	24%	11%	31%	10%	2%	22%
Scenario 2	5%	16%	32%	18%	16%	13%
Scenario 3	3%	25%	20%	20%	20%	12%

Conclusions

The current study developed a fuel life cycle (well-to-wheel) analysis to perform an in-depth assessment of various alternative buses, including hybrid, electric, and fuel cell buses at a city level, compared to diesel buses as a reference case.

The study considers the annual distance traveled as the primary input and considers three elements: total energy consumption by fuel type, GHG emissions, and criteria air pollutants.

The main findings of the current study are summarized as follows: First, both electric and fuel cell buses are characterized by reducing oil consumption in the TTW phase compared to hybrid and diesel buses. However, a significant increase in coal consumption was observed during the WTT phase for electric buses, due to the manufacture of batteries. Further, the extra usage of renewable energy has been particularly highlighted for electric buses within the WTT and TTW phases. Second, the hybrid buses emit slightly lower levels of GHGs than diesel buses during the WTT phase, while electric and fuel cell buses achieve zero GHG emissions during their operation. In terms of criteria air pollutants, electric buses emit relatively higher amounts of NO_x, SO_x, PM_{10}, and $PM_{2.5}$ during the WTT phase compared to the other options, while its emissions are significantly lower for hybrid buses. On the other hand, the electric and fuel cell buses in the TTW phase demonstrate not only the absence of NO_x, SO_x, CO, and VOCs as compared to diesel buses, but they also cause negligible amounts of PM_{10} and $PM_{2.5}$.

To ensure the sustainability of public transport fleets in terms of energy consumption and environmental impacts, several recommended measures to be considered, including the introduction of a bus rapid transit (BRT) system that will address challenges related to urban mobility, along with economic efficiency, flexibility, convenience, and safety concerns. This system has also the potential to support the transition to cleaner public transport, which leads to improved service for citizens, reduced congestion, and reduced air pollution. In this perspective, the modernization of the existing public transport fleet and improved infrastructure can be achieved via the coordination of the different operators involved in public transport. Also, the development of hydrogen-powered fuel cell buses in Morocco is particularly relevant in cities, because Morocco is expected to become a major exporter of hydrogen gas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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