

Well-to-wheel greenhouse gas emissions assessment for diesel and battery electric bus fleets based at the Technical University of Havana

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Abstract

Electric and hybrid powertrains are currently regarded as a set of more promising technologies for propulsion of vehicles with potential to reduce greenhouse gases (GHG) emissions from road transport. More cities are introducing their first electrified routes and system as pilot projects. However it is important to recognise the CO_{2e} intensity of electricity mix of each country. This study assesses the “Well-to-Wheel” (WTW) GHG emissions impact of replacing diesel bus fleet (DB) with battery electric bus (BEB) fleet in the Technical University of Havana (CUJAE). The WTW framework applied here considers both direct emissions from fuel combustion, as well as upstream emissions from fuel production and transport. The study includes the recharging of the BEB fleet using an ICE (Internal Combustion Engine) generation set, fed with landfill gas (LFG) from municipal solid waste (MSW) site near the University. The study also models recharging using the Cuban 2022 and future 2030 electric grid scenarios. The results show that there is a 595 gCO_{2e}/kWh reduction in WTW GHG emission when compared DB fleet to BEB fleet recharging from LFG genset when the lowest possible WTW emission values are applied. Then a 762 and 682 gCO_{2e}/kWh WTW GHG reduction when comparing DB with BEB fleet due to recharging from 2022 and the future 2030 Cuban electricity mix scenarios respectively. The study does not include an analysis of the global warming potential for reduction of methane from the LFG which would also support the shift to electric bus systems in place of diesel fleets.

Keywords: Well-to-Wheel, Greenhouse gases, Landfill gas, Electric bus

Resumen

Los sistemas de propulsión eléctricos e híbridos se consideran actualmente como uno de los grupos de tecnologías con potencial para reducir las emisiones de gases de efecto invernadero (GEI) del transporte por carretera. Cada día más ciudades están introduciendo sus primeras rutas y sistemas electrificados como proyectos piloto. Sin embargo, es importante tener en cuenta la intensidad de CO_{2e} del mix eléctrico de cada país a la hora de introducir estas tecnologías. En este caso el presente trabajo evalúa el impacto de las emisiones de GEI del pozo a la rueda (WTW) de la sustitución de la flota de autobuses diésel (DB) por una flota de autobuses eléctricos de batería (BEB) en la Universidad Tecnológica de La Habana (CUJAE). El marco WTW aplicado aquí considera tanto las emisiones directas de la quema de combustible como también las emisiones aguas arriba debidas a la producción y el transporte de este. El estudio incluye además la recarga de la flota de batería utilizando un grupo electrógeno ICE (Motor de Combustión Interna), alimentado con gas de vertedero (LFG) del depósito de residuos sólidos urbanos municipal (RSU), cerca de la Universidad. El estudio también modela la recarga utilizando la red eléctrica cubana de 2022 y la futura de 2030.

Los resultados muestran que hay una reducción de 595 gCO₂e/kWh emitidos al recargar la flota BEB con el generador a partir del biogás en comparación con el diésel. Luego al comparar la recarga usando LFG con la recarga utilizando el mix eléctrico actual y el del 2030 hay una reducción de 762 y 682 gCO₂e/kWh respectivamente. El estudio no incluye el análisis del potencial de calentamiento global para la reducción de metano, que también respaldaría el cambio a sistemas de autobuses eléctricos en lugar de flotas diésel.

Palabras clave: Huella de carbono, efecto invernadero, Gas de vertedero, ómnibus eléctrico

1. Introduction

The availability of electric heavy-duty vehicles (HDV) models is expanding in leading global markets. Buses were the earliest and most successful case of electrification in the HDV segment. The global electric bus stock was 600,000 in 2020 and there are several commercially available electric buses in the world market today [1]. The Cuban government is implementing short and medium terms strategies to introduce electric transport, and some hybrid and electric buses are running currently. They are Yutong brand and have been operating since 2017 in the capital, Havana. The environmental impact of electric vehicles strongly depends on country-specific electricity generation mix and can become more sustainable due to the increasing share of renewables. It was shown in [2] that sustainable electricity generation can also increase BEB's market share. The probable GHG reduction potential of electric buses in Havana city in relation to the entire transport sector would be relatively low, as buses represents just approximately the 10% of the total traffic flow [3] but we note that this mode moves the largest number of people daily by public transport.

Cuba relies heavily on oil use in the country's energy production and about two thirds of that oil used is imported [4]. The energy sector has been developing constantly in the last 60 years, achieving as the main result the distribution of electricity to 97% of the country. Also the growth of domestic oil production, is achieving about 47% of the total consumption and there has been a very gradual introduction of renewable energy technologies, with some positive results for demand side management [5]. According to the studies conducted by the Ministry of Energy and Mining (MINVAS) of the Republic of Cuba in 2018, the average CO₂ emission factor corresponding to the production of electricity from the non-renewable energy sources was 1,050 g/kWh, and 266 grams of fuel were needed to generate 1 kilowatt hour (kWh). It is assumed that by 2030 this emission factor will be reduced to 993 g/kWh [5]. The use of such large amounts of fossil fuels within the energy mix contributes to a whole range of issues that create serious negative externalities. These negative issues include: soil degradation, deforestation, pollution, loss of biological diversity and lack of potable water that have been identified as some of the main environmental problems in the country [6]. Several plans and projects have been applied to reduce the pollution impact, following the policy expressed in the National Environmental Strategy. Aligned with those policies adopted by the government, the Government Commission for the Development of the Renewable Energy policies for the period 2010–2030, it is planned to put into operation some power plants based on the renewable energy sources with an installed capacity of 2269 MW before 2030 [5]. Many of these actions directly impact on the capital city which is home to more than 2.2 million people, or approximately 18-21% of the entire population. Within the capital area there are two major academic institutions CUJAE and the University of Havana and both Universities play a role in being aligned the development of renewable energy systems.

The Technological University of Havana, CUJAE, occupies an area of 398 km² and more than 40 buildings. Created in 1964, it is the country's largest center for engineering and architecture studies in Cuba. On campus, there are classrooms, laboratories, libraries, conference rooms, several research centers, dormitories, dining services, administrative and post offices, medical services, workshops,

warehouses and bus depot. It has nearly 1,000 full-time professors and researchers, and 13 possible careers to enroll among its 9 faculties. In addition, in its surroundings there are human settlements with a high population density.

About 500 m from the University, there is a landfill site, which has an approximate area 350,000 m² and a height of 30 m from the ground (see Figure 1). In an uncontrolled "open burning" of waste there partially combusted materials such as paper, wood, plastic, textiles, rubber, waste oils and other residues, where the smoke and other emissions are released directly into the surroundings. There have been numerous food, air and water quality studies carried out in the area [7].



Fig.1 Map of the the CUJAE campus and the landfill site

The landfill site frequently catches fire and the cause is either uncontrolled waste management mechanism, or the product of self-combustion processes. In this type of incineration, the combustion is not controlled to maintain an adequate temperature, so the residence time necessary for complete combustion is not guaranteed. The site then creates large plumes of dense smoke with several GHG emissions being released, especially CO₂, methane (CH₄) and nitrous oxide (N₂O) to the atmosphere. The presence of that smoke, as is in Figure 2 observed, also generates the lack or collapse of oxygen that occurs in the human body; and its consequences translate into specific symptoms such as nausea, headaches, dizziness, convulsions, or vomiting, depending on the concentration of the gas and the time of exposure [8]. Previous studies carried out in the area have shown that the rate of emissions of particulate matter (PM₁₀) from the landfill site is 1.3×10^{-5} g/m² [9]. Using this emission rate and the area occupied by the landfill, the emissions are around 4.55 g/s (393.12 kg/day) which is significant.



Fig.2 Smoke from combustion in the landfill site

Figures 1 and 2 also highlight the fact that the CUJAE area is a major transport interchange area being a key corridor (route A4) to the main airport and further south, as well as a critical destination for many students and workers in that province (Boyeros).

In Cuba the government set out a strategic policy in transportation framework for next years. The main transport measures were to:

- Upgrade the main ports used for international trade.
- Increase urban, suburban, rural and intercity transport (buses and railways).
- To improve the road network and infrastructure associated with it.

The key policy for consideration in this study is mainly about the type of urban bus provision most appropriate to achieve the aims above, but with battery electric one must also consider the required infrastructure for charging. A short description of the whole vehicle fleet shows how buses fit into the overall vehicle mix. The main vehicle fleet in Cuba tend to be one of this four types; there are privately owned cars (generally US cars bought before 1959, some vehicles from the same decade from the Eastern Europe and the USSR, and other old models), which were sold to some officials, university graduates, national vanguard workers and other public and private sector workers. There are also Government-tourist cars (that are usually Asian-Western European-built cars from 1990 onwards). Also, there are those vehicles that tourism has discontinued because they completed their exploitation time and were sold in certain agencies as second-hand vehicles. Heavy vehicles for transport before 1959 came from USA, and then, in the 70s and 80s from the USSR, and currently the largest amount comes from China. It is common today to find vehicles from Dayun, JAC and Foton brands, among others in the streets. In the case of urban buses, the most abundant brand is Yutong. These 4 categories can be thought of as old cars, median age cars, modern cars and buses. There are also heavy trucks and motorbikes in the vehicle mix, but here we focus mainly on the Yutong bus as the prime mover for people in Havana.

It is easy to distinguish the pollution caused by transportation in Havana, and as stated above the transport fleet is comprised merely 50% by old and median age cars (1949-1990). Hourly fluctuations of traffic flow produce wider and visibly distinguishable peaks; during the morning, traffic increases until 11:00 am and then subtly decreases prior to 5:00 pm, when a new peak appears, figure 3. The figure also shows that buses represent merely the 10 % of total traffic flow, with an average of 100 v/h [3]. The majority of these buses are manufactured by Yutong.

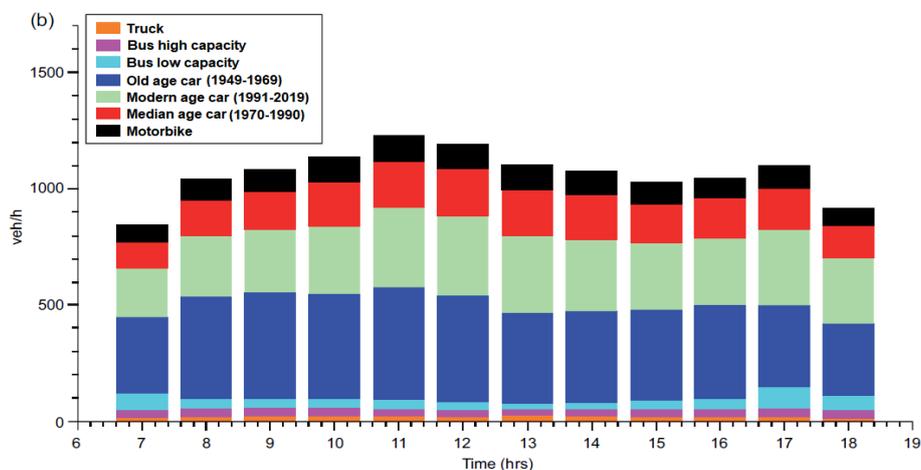


Fig.3 Hourly fluctuations of traffic flow in Havana

The Yutong ZK6125BEVG11 model is a 12.17 m full electric zero emission bus which runs through the streets of Havana since 2017. It shares the same driveline as all other Yutong electric buses, with approximately 130,000 Yutong electric buses worldwide. In Oxford (England, UK) it is configured predominately as a double deck city bus, surpassing the range required for a bus to run in service all day long without a recharge; the daily route requires over 14 hours, 140 miles plus service with energy capacity to spare, providing a potential distance of more than 200 miles on a single overnight charge [10]. Given that there is a demand for more than 1000 urban buses in Havana, the focusing on battery buses could have a significant impact in terms of acceptance and use of electrified fleets.

The electrification of the transportation would be a significant step in reducing GHG emissions [11, 12] as shown in other cities and studies. This study assesses the WTW GHG emissions impact of replacing the DB fleet of CUJAE University with a BEB fleet. The WTW GHG emissions assessment of BEB fleet include recharging from Cuban 2022 and future 2030 electricity generation mix, and from biogas generation set fed with LFG from the nearby landfill. Although this is a small fleet it has the potential to be an important step towards further electrification of areas of transport.

2. Methodology

This section outlines how the various bus fleets are configured the calculations undertaken to derive the overall GHG emissions and impacts. The Yutong ZK6125BEVG11 (battery electric) bus [13] is compared with the Yutong ZK6118HGA diesel bus, which also is part of the fleet of metropolitan buses in Havana [14]. The BEB model is fitted with a 285 kWh battery, and capable of daily operational range of more than 200 km on a single charge, subject to their specific operational conditions. The diesel bus has a fuel capacity of 270 liters and complies with the EURO III emission standard regulations. Both buses are rigid type, 12 meters long and have a capacity for 90 passengers. The characteristics of the buses are presented in Table 1.

Table 1. Battery electric and diesel bus characteristics

Bus type	Model	Engine-Motor power (kW-rpm)	Battery Capacity (kWh)	Range (km)
BEB	Yutong ZK6125BEVG11	200-2800	285	200-220
DB	Yutong ZK6118HGA	213-2100	n/a	630-675

Schedules and Recharging modes

The University fleet is composed of five dedicated diesel buses, for the daily transportation of students and professors, with the routes shown in the table 2. Pax is the abbreviation for passengers. The BEB consumption is 140 kWh/100 km and the DB is 40 L of diesel/100 km. Overnight charging for BEB fleet would be implemented in the bus depot, on campus, using fast chargers (50 kW), when the buses are not in service. Both diesel and electric fleet have a fixed running schedule, working 226 days in the year, in the working days from September to July. Every diesel bus route is substituted for one electric bus on the same route. All the buses complete 4 journey per day. The first one is from the driver's house to the University campus from 5 to 7 am in the morning. The second one is from the University to the end of each route (1 pm to 3 pm) and then all buses return to the University (3 pm to 5 pm). Then, the last trip departure at 5:30 pm from the University campus to the end of each route (7:30), and then goes to the house of route's bus driver, which adds about 10 km more average for each route. It is the same schedule (Monday to Friday) from 5 am to 8 pm. Overall every bus works about 9 hours every day and travels (on average) 131 km as shown in Table 2.

Table 2. Bus transportation routes, CUJAE

Route	Pax per bus	Pax daily total	Bus Stops	Trip distance (km)	Daily trips	Daily traveled distance total (km)
Vedado	90	360	13	29 + 10	4	126
Cotorro	90	360	5	31 + 10	4	134
San Agustín	90	360	11	30 + 10	4	130
Santiago	90	360	7	35 + 10	4	150
Santa Fe	90	360	9	33 + 10	4	142
Total	450	1800	45	158 + 50	20	682

The longest trip is the CUJAE-Santiago route, requiring 150 km daily, needing 195.0 kWh to travel this distance per day. The battery is 285 kWh capacity, so it can power the whole trip and still have ~90.0 kWh left in the battery (~30%) at the end of the journey. Then using a 50 kW charger provided by Yutong, the batteries of this BEB can be recharged to a full reading in 4 hours.

Using just one 550 kW biogas genset and three 100 kW electric chargers with 2 outlets of 50 kW each, it is possible to recharge the 5 BEB in 4 hours every day (from 8 to 12 am). The generator can be stopped for maintenance preferably during university closure periods. For the remaining 20 h of the day, the generators could deliver the electricity to the grid. The consumption of the engine is 314.3 m³/h of LFG at full load, with a 35% efficiency. Then the daily biogas needs for recharge the BEB fleet is 1256 m³. In case the generator sends energy to the grid in the 20 h left it can deliver about 11000 kWh of electricity each day. During weekends it could be kept running 24 hours delivering the energy to the grid and also reducing the total amount of methane being released to atmosphere. The landfill site emits around 5000 m³/h of biogas [15], and recovering the 50% of that volume (2500 m³/h) would require multiple generator sets, and this type of installation should be considered.

Landfill gas from Municipal Solid Waste

Landfill gas (LFG) is produced naturally when organic material is decomposes in the landfill materials. The LFG is mainly composed by methane (55%) and carbon dioxide (45% by vol.), with a density of 1.13 kg/m³. Other substances such as ammonia, nitrogen, hydrogen sulphide, dust, siloxanes and water vapor are also present. In general, 1 Nm³ of biogas, is characterized by a lower heating value of 21.5-23.5 MJ/Nm³ (5-6 kWh/Nm³). However, before converting biogas into electricity or heat or both of them, it is fundamental to remove impurities and harmful substances (droplets, dust, mud, trace gases). The LFG used is the present study coming from the Municipal Solid Waste Landfill (MSW) near the CUJAE University campus (500 m distance), located between 23°06'12"N and 82°21'23"W. The landfill was assumed having an active area at ground level of 35000 m², a lift height of 30 m and a compressed MSW density of 0.8 T/m³. Operations started in 1975 and then it should have closed in 1995 after operating for 20 years, but it is still currently functioning. During its whole life (1975 to present) the site has received more than 20 million tons of garbage from 10 municipalities of Havana, of which approximately 40% is MSW. The current thickness of the MSW is variable but reaches a maximum depth of 25 m [9]. At present, the landfill has a biogas recovery system based on natural extraction via 8 extraction wells that are interconnected. The network extracts biogas that is thermally destroyed by four burners without power 24 h a day, each with a capacity of 17 m³/min. According to the U.S. Environmental Protection Agency (USEPA) model of biogas generation, the biogas maximum flux of the site was estimated at

5000 Nm³/h for 2015 (Figure 4). Assuming a recovery efficiency of 50%, roughly 2500 Nm³/h of biogas could be recovered [16].

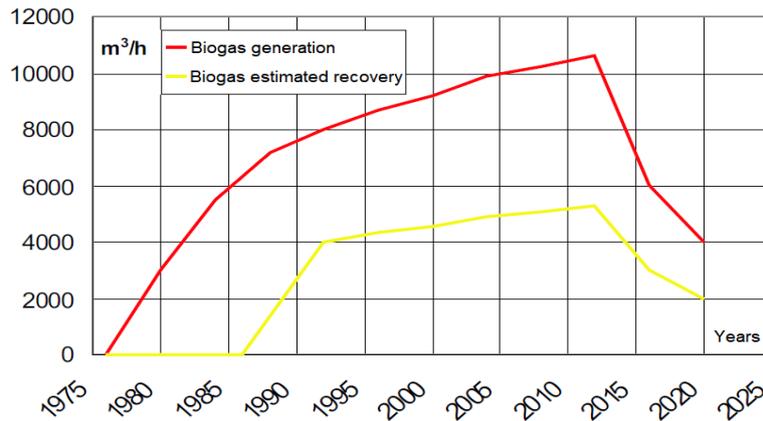


Fig.4 Projection of the generation and recovery of the biogas at the landfill

As presented above, the existing situation in the landfill gives rise to direct venting to the atmosphere of 5000 Nm³/h of biogas (120000 Nm³/day); containing 55% CH₄, represents 74.6 kg of CH₄ per day. Capturing and combusting the CH₄ contained in the biogas in the engine of the generator, would become in CO₂, with less than 80 times its warming potential in 20 years.

Assessment of WTW energy consumption and GHG pollutants

The term “Well-to-Wheel” refers to the entire process of energy flow, from the mining of the energy source to a vehicle being driven. Specifically, the WTW process of diesel vehicles is a seven-step process consisting of: extraction (well), transport, refining, distribution, engine combustion, power delivery system, and the wheels. This can be calculated by using Eq. (1). On the other hand, the WTW process of BEBs includes nine steps: Extraction (well), transport, refining, distribution, power generation, power transmission and distribution, charging, motor, and the wheels. Thus, the well-to-wheel process of BEB consists of two major steps. The first is the process of mining the energy source and transporting it to the power plant (well-to-power plant), and the other is the process of transmitting the electricity to the car and driving the car using that electricity (power plant-to-wheel). Therefore, the well-to-wheel GHG emissions from a BEB is the sum of the GHG emissions of the well-to-power plant (WTT) and power plant-to-wheel (TTW) processes. This can also be calculated by using Eq. (1).

$$GHG_{WTW} = [GHG_{WTT} + GHG_{TTW}] EC \quad (1)$$

In this equation, DB GHG_{WTW} is the total GHG emitted from the WTW viewpoint and it is measured in units of g CO_{2e}/km. The terms GHG_{WTT} and GHG_{TTW} represent the total GHG emitted in the WTT and TTW processes, respectively, and are measured in units of gCO_{2e}/kWh. Then the energy consumption (EC) is measured in kWh/km. For the calculations, the energy consumption unit (L/100 km) of DB can be converted to the fuel consumption unit (kWh/100 km) of BEB, table 4. Standard conversion factors state that 1L of diesel is equivalent to 10.0776 kWh of electricity, then in this study a diesel liter equivalent (DLE) energy consumption taking into consideration is 1L diesel = 10 kWh energy. As can be seen, DB consumes about three times more energy than BEB for each kilometer traveled.

Table 4. Urban operation energy consumption for GHG emissions modeling (kWh/km / DLE/100km) [17]

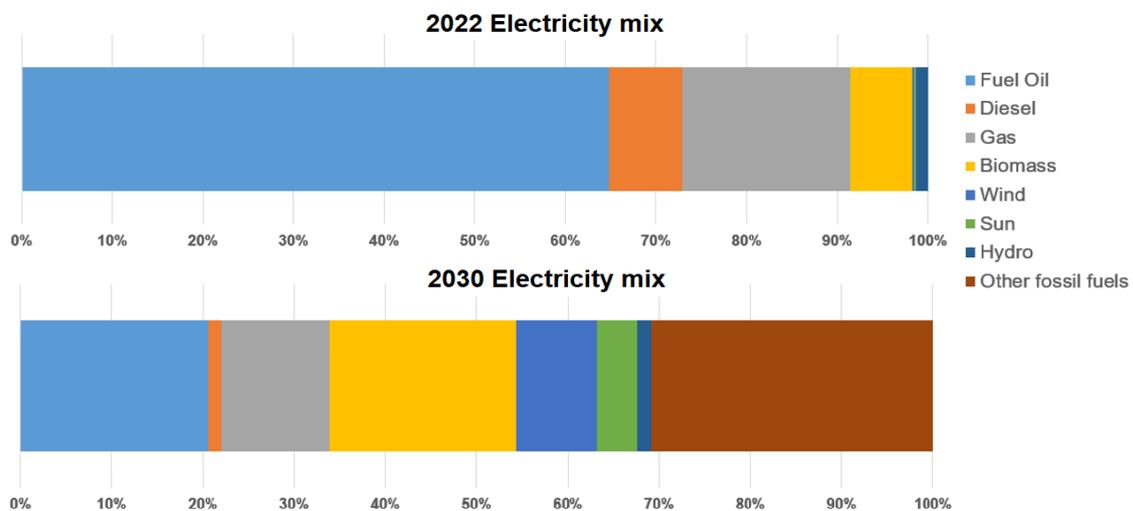
Bus type	TTW Energy consumption (kWh/km - DLE/100km)
DB	4.0-40.0
BEB	1.4-14

Well-to-wheel GHG settings

In the WTW framework used in this study, the fuel carbon intensity of the GHGs emitted directly through the combustion of fuels in bus engines is evaluated, as well as upstream emissions resulting from fuel and feedstock production and transport. For carbon intensity values, GHGs include carbon dioxide, nitrous oxide, and methane; 100-year global warming–potential (GWP) values are used for conversion to CO₂e units. In this case study the BEB acts an alternative, which can be free of fossil fuels if electricity generation comes from renewable sources. It is assumed that LFG has the same overall potentials as biogases derived from biodigesters.

Well-to-Tank GHG emissions

While the electricity production in Cuba is largely based on oil currently, it is predicted to be 24% renewable energy for 2030, as can be observed in Figure 5. The carbon intensity values used for electricity served (production and distribution) for 2022 and 2030, is 1050 g/kWh and 993 g/kWh respectively [5].

**Fig.5** Cuban electricity mix for 2020 and 2030

The results calculated using the WTW GHG emission factors for both power sources used for BEB recharge, show that there are 506 gCO₂/kWh WTT GHG in BEB fleet when recharging using LFG, and 1050 and 993 gCO₂/kWh WTT GHG when BEB fleet is recharging from 2022 and 2030 Cuban electricity mix respectively [5]. In the case of DB fleet, it emits TTW 271.2 gCO₂e/kWh and WTT 63.4 gCO₂e/kWh [18], Table 5. Although not shown here (in table 5) if one treats LFG as fossil fuel and accounts for total CO₂ produced then the WTT values rise by about 3-3.3 times larger than the biogas standard values (see BEB w/LFG genset). Even at this elevated level of ~500-570 gCO₂e/kWh, the lower overall carbon intensity of gas as a feedstock is evident.

Table 5. WTW Carbon intensities for each scenario

Fuel-Electricity	WTT GHG (gCO ₂ e/kWh)	TTW GHG (gCO ₂ e/kWh)	EC (kWh/km)	WTW GHG (gCO ₂ e/km)
DB	63.4	271.2	4.0	1338.4
BEB w/2022 grid	1050.0	N/A	1.4	1470.0
BEB w/2030 grid	993.0	N/A	1.4	1390.2
BEB w/LFG genset	506.0	N/A	1.4	708.4

The results calculated here do not include the impact of removing methane as GHG which will further support the use of LFG conversion into electricity. The cost of methane diverted could be substantial and will be considered in future work.

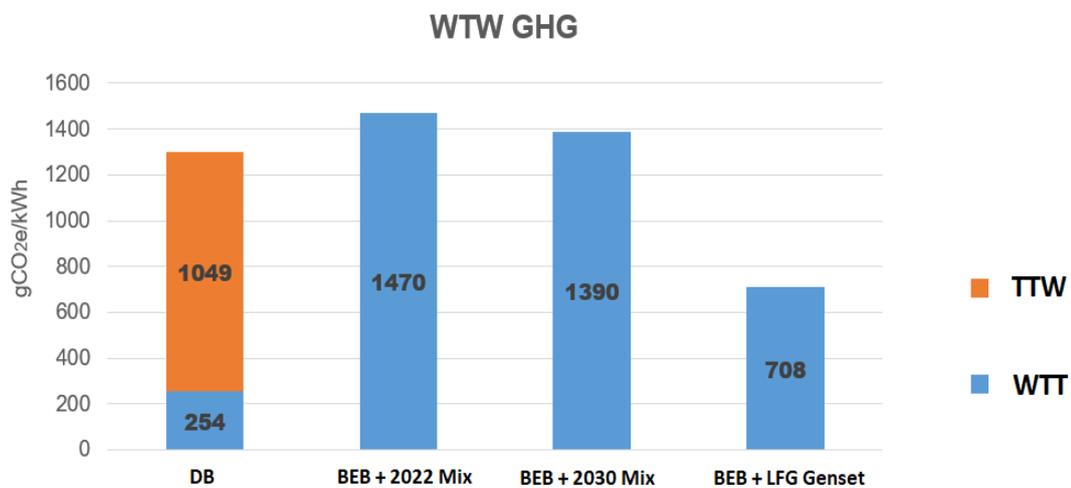


Fig.6 WTW Carbon intensities for each scenario

3. Conclusions

This study analyzed the differences in GHG emissions from a WTW perspective associated with the possibility of replacing the diesel bus fleet with battery electric bus fleet in Technological University of Havana (CUJAE). Using the Cuban 2022 and 2030 electricity mix scenarios for recharging only marginal gains can be made in terms of CO₂ savings due to the high level of fossil fuels in the country’s energy mix. When recharging using LFG in an internal combustion generation set was evaluated much lower results are observed. Results show that from TTW the BEB uses 65% less energy per kilometer than DB do, and emit no GHG comparing with the 1303 gCO₂e/km emitted by every DB. In the WTW feature DB fleet emits 167 and 87 gCO₂e/km less than BEB when recharging from 2020 and 2030 Cuban energy mix scenarios respectively. In the case of BEB fleet recharging using the LFG it emits almost 2 times less GHG than DB fleet. Overall the WTW results show that using Cuban energy mix to recharge the BEB fleet it is not a good method for decreasing the environmental and health impacts caused by conventional diesel buses. In the case of recharging from an LFG generation set much lower emissions can be achieved and there are large benefits in relaxing escaping methane gas and converting it to electricity, also it is possible to deliver energy to the grid.

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Conflict of Interest

The authors declare no conflict of interest. The information included in this manuscript is a result of a research about the application of a Cuban electricity mix and LFG genset for recharging a captive fleet of electric buses. This manuscript is not published and has not been submitted to any other journal.

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