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Planning a Transition to Electrification of Public Transit Systems: Learnings from the Bus Rapid Transit System of Metrobus in Mexico City

APEC Energy Working Group

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CASE STUDY

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EXECUTIVE SUMMARY

Increasing the energy efficiency of the transport sector through interventions of electrification and institutional coordination with the energy sector is key to increasing social, economic, and environmental impacts in APEC economies. Particularly, the benefits of these types of interventions become increasingly relevant to reducing the levels of air pollution in urbanized areas, with measurable consequences for public health and fighting climate change.

Mexico City is a city in constant demographic growth and this growth plays a determining role for the development of the Mexican economy and the Latin American region, while also presenting serious contamination problems, most of which are due to the transportation in the city. The transport sector is the sector with the highest consumption of fossil fuels, representing more than 60% of the energy demand of the city; this means the transport sector is related to the emissions of particulate matter (PM10 and PM2.5), nitrogen oxides, and carbon dioxide. However, Mexico City has great potential for making use of renewable sources of energy and promoting the transition to electric vehicles, including for public transit.

Mexico has committed to a 22% reduction in emissions of greenhouse gases (GHG) for 2030. The goals established to comply with this aim to bind the energy and transport matrices toward power generation based on renewable sources, promotion of multimodal passenger transport, and modernization of the vehicle fleet. In this context, a series of new tax and environmental public policies have been placed that encourage the adoption of electric vehicles in the city through tax exemptions, movement and access restrictions, and access to differentiated benefits. These actions, although recent, have already produced impacts that could convey deeper policy changes and will be analyzed in this case study.

This project aims to build capacities in both APEC and non-APEC developing economies to energize the adoption of sustainable mobility solutions through integrated approaches to transport and energy. Among other actions, this project seeks to develop a case study to document the progress of an APEC Latin American economy in the development of energy efficiency strategies in the transport sector. Among the APEC Latin American economies, only Chile has achieved the implementation of an electric fleet at scale in the public transit system. Therefore, an initiative of planning and early implementation was selected to identify opportunities and valuable learnings for the sector. During 2020, the Metrobus entity carried out a series of actions to incorporate 10 electric buses in one of their corridors.

This case study focuses on the analysis of a partial vehicular fleet modernization pilot project in Line 3 of the Rapid Bus Transit (BRT) system of Metrobus, which comprises the deployment of the first 10 electric buses and afterward the substitution of buses that have reached the end of their service period. Until now, the Metrobus system was functioning exclusively on buses with internal combustion engines (ICE), a fleet that is made up of seven lines that have an extension of 140 kilometers and 239 stations that provides a daily demand of approximately one million passengers.

The deployment of electric buses on Line 3 of Metrobus is the initial step in the pilot phase of a project that envisions a whole transition of the BRT system. The first 10 buses will be put in service between the first and third quarter of 2021 (during the execution of the current study), whose operational results must inform the selection criteria to be used in the development of an immediate phase to replace the buses that, according to the current operational rules, must be taken out of service from the BRT system during 2021 for reaching the end-of-service period.

This case study highlights the strategies and actions that allowed the successful execution of this first stage in the replacement of traditional buses using ICEs. The analysis emphasizes the methodology for choosing the technology and the necessary recharging infrastructure, including a discussion of the impacts of the replacement plan, such as cost savings and reduction of pollutant emissions.

The case shows that electrification projects for massive passenger transportation systems, such as the Metrobus BRT system, require a specific study of current operating conditions to identify opportunities for the implementation of electromobility. This experience demonstrates that BRT-type systems, due to their configuration and mode of operation, present important advantages when considering battery-powered electric bus or battery electric bus technologies. To develop transition plans of these characteristics, it is necessary, on the one hand, to consider the execution of pilots to establish the initial parameters for the adequate selection of the technology, the recharging infrastructure, and the new operating conditions. The evaluation of the results in the steps of the pilot project allows, in turn, to define iteratively the scaling criteria for the subsequent stages of deployment of the units and associated infrastructure.

The study showed the key aspects for the implementation of electric buses in a public transport system such as Metrobus: (1) the importance of choosing the *ideal corridor* and its fundamental characteristics, (2) *the planning of the replacement stages* of the internal combustion fleet, (3) the *technical characteristics of the electric buses* to be implemented based on the operational characteristics of the BRT system, and (4) the *recharging system*. Likewise, the study shows that *staggered progression* enables the fleet managers to learn from each addition, with data, costs, and maintenance, thus enabling even more scale-up by sharing these with others within Metrobus.

The biggest challenges highlighted in the case study -linked to massive deployment of electric buses- will lead to a higher demand for electricity, which, if not planned and managed adequately, could burden the city's power distribution system. The results showed that increasing transport electrification of transport and, therefore, an increase in electricity demand, necessarily implies a greater development of recharging infrastructures in such a way that they do not overload the networks while exploiting the potential of renewable energies.

CONTENTS

INTRODUCTION

As economies become more and more industrialized and the population migrates and concentrates in urban areas, transportation needs and energy consumption levels increase accordingly. On the other hand, the incredible ongoing technological progress could, in many ways, revolutionize our perception of cities, specifically how we live them and how we move.

The World Health Organization (WHO) estimates that 90% of the world's population lives in a town where the air contains a high level of gases that are harmful to health, mainly due to the low efficiency of the energy and transport matrix. The consequences of air pollution generate approximately 4.2 million victims annually due to cerebrovascular problems, heart disease, lung cancer, and chronic respiratory diseases (WHO, 2018).

In this context and on the way to a better quality of life and environmental and energy sustainability in urban centers, APEC firmly believes that electric mobility plays a key role, both in the public and private sectors. Improving energy efficiency in the transport sector can also make a significant contribution to keeping the global average temperature rise below 2ºC concerning preindustrial levels, continue efforts to limit temperature rise to 1.5ºC, and achieve optimization of economy's energy consumption. It is therefore imperative that APEC economies, which account for about 60% of global energy consumption, find ways to reduce the use of fossil fuels to meet energy demands (APEC, 2020), among them transport energy demands.

The project's overall objective, this study's framework, is to build the capacity of APEC and non-APEC developing economies to better support goals in achieving sustainable mobility solutions in urban cities via integration of the transport and energy sectors. The specific objective of this case analysis is to document the progress of a Latin American APEC economy, particularly in the case of the Mexico City BRT system, in the implementation of strategies developed to increase the energy efficiency of the transport sector through its electrification and strengthen the mechanisms and institutional coordination between the transport and energy sectors.

A factor that plays in favor of the transport/energy relationship in sites like Mexico City is the high potential to generate renewable energy and adequate conditions for the use of electric vehicle systems in massive passenger transport to deliver its greatest benefits of energy efficiency, reduction of negative socio-environmental impacts, and sustainability of the system. The Government of Mexico City has on its agenda several projects related to the electrification of transport modes and the energy efficiency of those systems.

This study analyzes a pilot for the first phase of modernization of the vehicle fleet of Metrobus[1] Line 3 using electric buses to later lay the foundations for extending the scope of the project to total electrification of the line and other lines in the future. The first part of this report contains the description and analysis of the energy situation and the public transport network in the city, forming the database for the study and analysis of the

[1] The Metrobus is registered internationally as a Rapid Bus Transit system (BRT).

project. The second part presents the analysis of the case study and the results of a series of energy and transport scenarios.

Connection Between the Case Study and Previous APEC Projects and the Synergies Between Other Programs

This study is placed within the framework of APEC initiatives to improve the quality of the energy matrix, taking into consideration several factors, including resilience to disasters, life cycle costs, and environmental impacts. Specifically, it is linked to other APEC projects that study economic inefficiency, local environmental pollution, and the enormous negative social consequences generated by the dependence on fossil fuels for transport and energy services.

One of these projects is the "*Roadmap for the Integration of Sustainable Energy and Transport in Small Islands,*" which studies transport and mobility in the APEC islands mainly based on ICE vehicles. The result of the study highlighted the need to transition to a transportation system based on electric vehicles linked to the exclusive use of renewable energies on a large scale. As in the case of Mexico City, the APEC islands have enormous renewable energy potential and their transportation and energy systems can rapidly decarbonize. A deep transition toward sustainable transport and energy systems could generate a reduction in public subsidies, improvements in public health, increased quality of life, increased citizen participation, new and better employment opportunities, and mitigation and climate resilience.

As the first component in the design of the planning of the sustainable transport and energy transition in the islands, the project suggests the elaboration of a Sustainable Mobility Plan with a focus on the interested parties, a process that involves a phase of preliminary work, a strategy development process, and the design and implementation of concrete transformative measures. The adoption of electric vehicles powered by renewable energy is a key component of the broad set of applicable measures. However, a convergence of Avoid-Shift-Improve approaches is necessary to achieve a successful deployment of electric mobility in the transport ecosystem, in other words, the complementarity of actions allowing to synergize the benefits of each strategy.

As well as in the APEC islands project, in this study, the public transport sector plays an important role in the successful implementation of electric vehicles (and supporting infrastructure), and the "improve" measures are designed to raise the efficiency of emissions from the vehicle fleet. A second component in the design of sustainable energy and transport transition is the generation of a plan that allows legislators to select the most beneficial energy and transport integration scenario based on specific criteria.

It worth highlighting that public policies are essential for the advancement of sustainable energy and transportation. An effective combination of governance and regulatory and financial instruments can reduce investment risks in both sectors and create an attractive market environment for developers, financiers, and implementers of sustainable energy and transport solutions. Specific goals and objectives, concrete policies and measures, as well as effective governance processes, need to be designed and implemented in close cooperation with island stakeholders, or, in this case, the city's stakeholders.

CONTEXT

Mexico City is located on a plateau, better known as *Cuenca de México*, and occupies an area of 1,495 km^2. With a population of 8.851.080 inhabitants in 2010, it is inserted in a metropolitan area made up of 60 other suburban municipalities whose urban footprint can be seen in Figure 1.

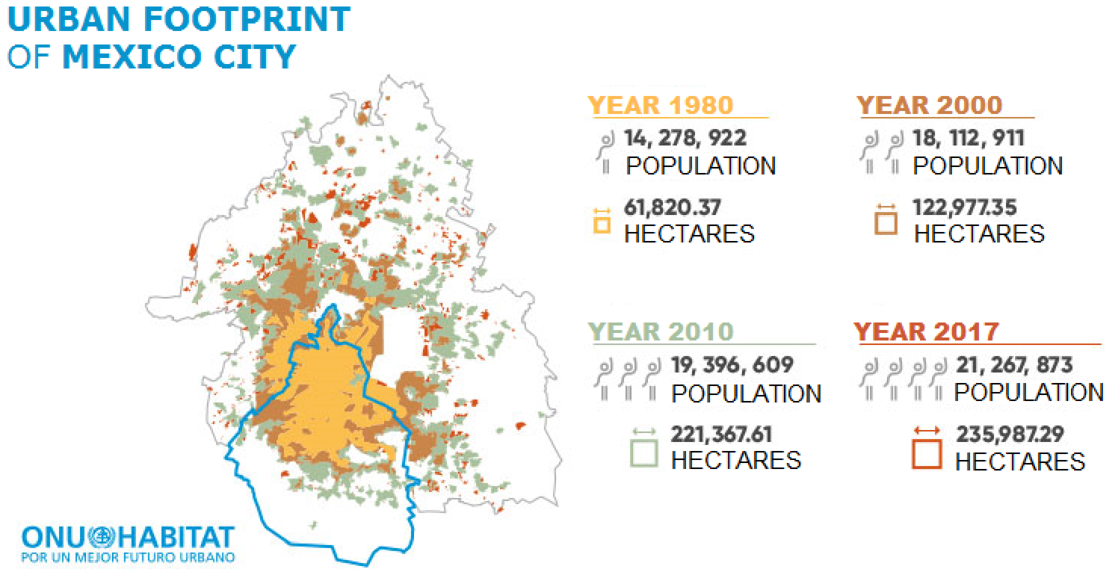

Figure 1. Urban footprint growth of the Metropolitan Area of the Valley of Mexico (in light blue line, district of Mexico City). Source: Own elaboration based on https://onuhabitat.org.mx/index.php/superficie-de-cdmx-crece-a-ritmo-tres-veces-superior-al-de-su-poblacion.

Mexico City holds the eleventh position in the world of the localities called "*Global Cities*[2]" that gather a series of characteristics derived from the effect of globalization, their level of urbanization, and their direct and tangible effect on world affairs that transcend the socio-economic environment and generate influence in cultural and political terms (Government of Mexico City [CDMX], 2019).

The economic relevance of the city is such that it is above the gross domestic product (GDP) of several economies in the region and has a high growth potential due to the global growth trend of megacities. These trends make it possible to project demographic growth and a greater potential to attract investment (National Institute of Statistics, Geography, and Information[3] [INEGI], 2010).

Accordingly, Mexico City represents 16.4% of the economy's GDP, as seen in **¡Error! No se encuentra el origen de la referencia.**, which makes it the district with largest contribution to their Mexican economy. The city's economic activities are concentrated around commerce, financial and insurance services, transport, and tourism. These activities (tertiary ones) contribute little more than 90% of the total GDP of the City.

[2] In the world there are only 10 cities classified as more relevant than CDMX: London and New York classified as Alpha ++ cities, and Hong Kong, Paris, Singapore, Tokyo, Shanghai, Chicago, Dubai, and Sydney as Alpha + cities.

[3] From Spanish: *Instituto Nacional de Estadística, Geografía e Informática*.

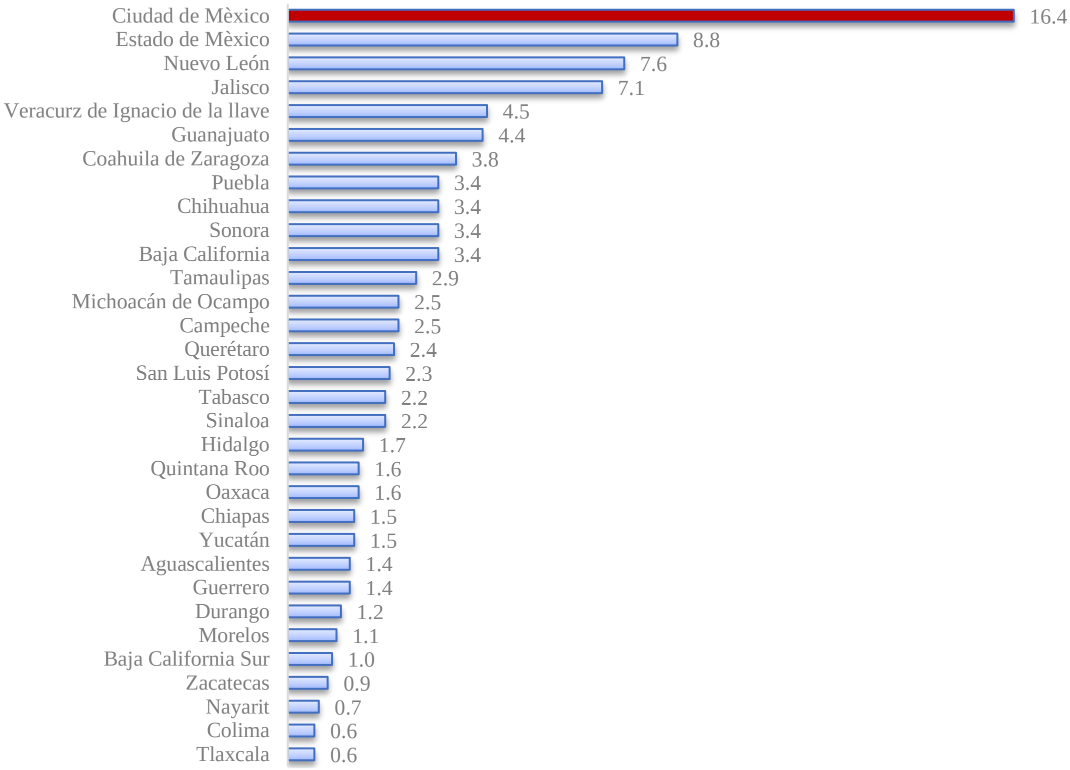

Figure 2. GDP by the state in 2018 [%]. Source: based on data from INEGI.

In the last years of the last century, the city and its metropolitan area, due to dangerous levels of pollution and mobility problems related to a high demographic concentration, has experienced a necessary decentralization of industrial transformation activities. Most industries have moved to nearby cities favoring the growth of this activity in other states. However, the levels of pollution in the city remain high.

According to the Organization for Economic Cooperation and Development (OECD), Mexico currently spends almost US$40 billion on health costs caused by pollution, and half of these are directly attributable to the transportation sector (EUROCLIMA 2016). Therefore, it becomes extremely relevant for the city to work on strategies for decarbonization and energy efficiency of urban transport, taking advantage of the contextual conditions that would allow the adoption of electric mobility.

Mexico Energy Matrix

The energy matrix of an economy includes all the energy available to be transformed, distributed, and consumed. It is a quantitative representation of the energy supply, that is, of the number of energy resources. The analysis of the energy matrix is fundamental for the planning of public transport because it allows analyzation of how rationally natural resources are being used. Oil and its derivatives have the largest participation in the matrix of Latin American economies.

According to a study conducted by Inter-American Development Bank[4] (IDB) in 2013, the renewable energy endowment of Latin America and the Caribbean is large enough

[4] From Spanish: *Banco Interamericano de Desarrollo (BID).*

to meet 22 times their projected electricity needs by 2050. This would allow them to meet all their electricity needs using renewable resources. The lower prices due to the increasing implementation of new technologies have made renewable resources more of a viable alternative. Renewable sources such as solar, geothermal, wave power, wind, and biomass in the region could produce up to 80 PWh[5] of electricity. One PWh is equivalent to 1 million kWh, about three times the annual Mexican electricity consumption.

Although investments in renewable energy have been limited in the economy, some new energy ventures are underway. Mexico is the fifth-largest producer of geothermal energy in the world, while biomass, solar, and wind energy projects are now growing (Secretariat of Energy[6] of Mexico [SENER], 2020).

Mexico's electricity generation corresponding to renewable sources is still limited, which is of utmost importance for electric-based mobility when the objective is to decarbonize transport. Figure 3 shows the constitution of the energy matrix in terms of electrical capacity by type of source where around 85% of the matrix continues to be dependable on fossil fuels and subproducts.

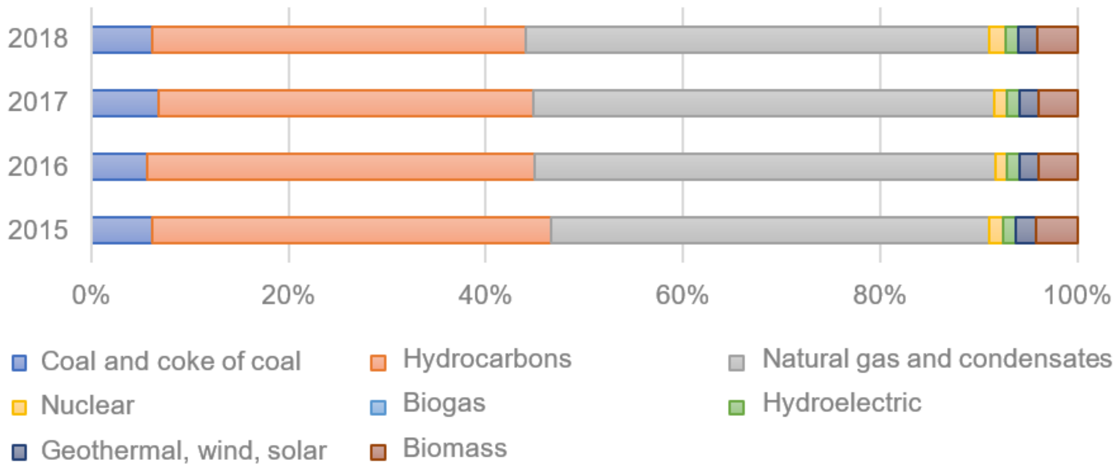

Figure 3. Electric capacity by type of source in Mexico. Source: Own elaboration based on information retrieved from EIA 2018.

This is worsened by the low quality of the electrical energy distribution networks, which can represent a barrier to the massification of electric mobility. In 2015, the World Bank generated a ranking of the quality of electricity supply in each economy, in which the highest quality service has no interruptions or voltage fluctuations. World ranking values assume values between 1 and 7, where the higher the value, the higher the supply standard. In Latin America (Figure 4) the average is the same as the world average (4.5), while developed economies have indices above 6 (UN Environment 2016).

[5] Petawatt hour (1,00e+09 MW).
[6] From Spanish: *Secretaría de Energía - México (SENER).*

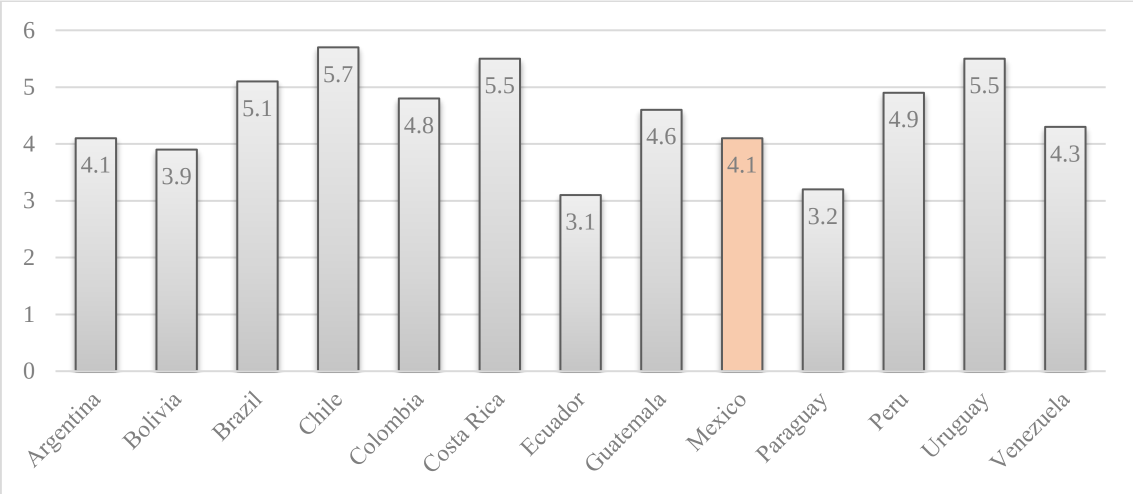

Figure 4. Electricity supply quality index. Source: Own elaboration based on information from World Bank, 2015.

Public Energy Policies and Connection With Public Transport

According to the 2014 National Inventory of Greenhouse Gases and Compounds, direct GHG emissions in the economy amounted to 729.1 megatons of CO_2 equivalent (NDC LAC, 2020), of which the highest contribution is from the transport sector (26%), followed by the generation of electricity (19%) and the industry. The distribution of emissions in the transport sector can be seen in Figure 5, along with estimations for future emissions.

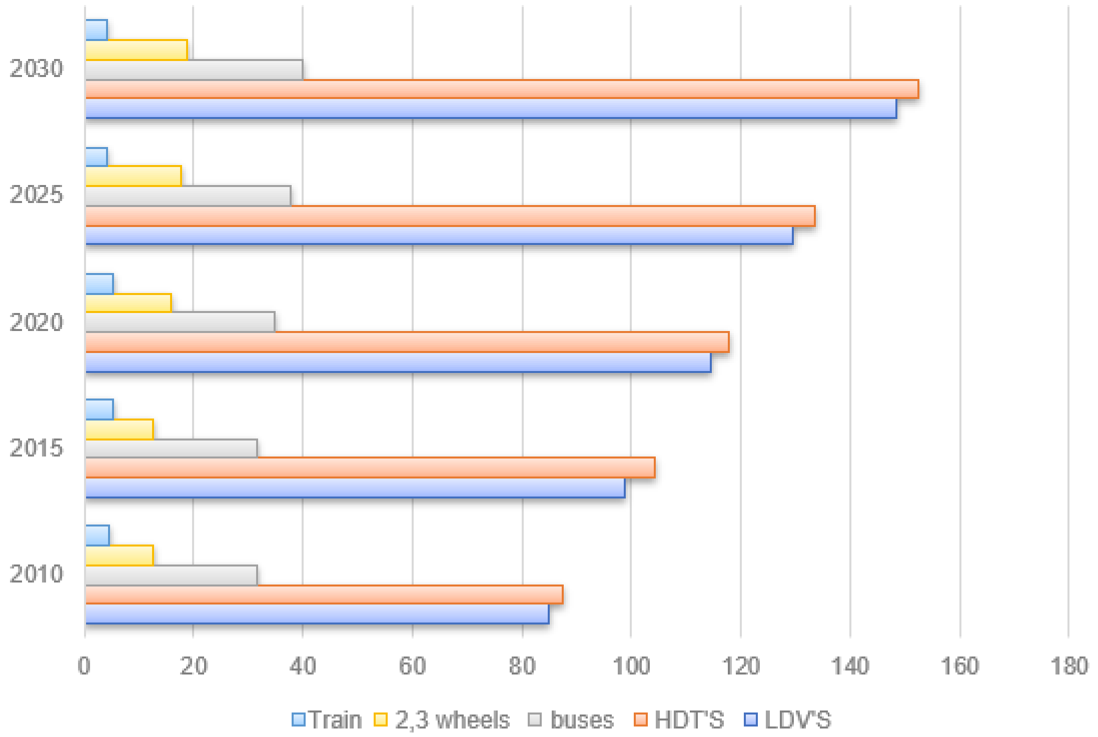

Figure 5. Estimation of emissions from the transport sector by vehicle type in Mexico (HDTs: heavy-duty vehicles; LDVs: light-duty vehicles). Own elaboration based on information provided by The International Council on Clean Transportation, ICCT 2014.

The inventory of emission of Mexico City (2016) produced by the Secretary of Environment of the City (see Table 1), reports that registered GHG total emissions were 22 megatons of CO_2 equivalent, including local jurisdiction sources. The inventory states that 60% of those emissions are associated to transport.

Source	Emissions [t/year]									
	PM10	PM2,5	SO2	CO	NOx	COV	NH3	CN	Toxics	CO_2eq.
Punctual	890	662	92	904	2.197	13.288	17	100	6.167	1.079.863
Area	3.775	1.518	629	37.305	6.171	113.668	13.935	58	35.411	4.581.392
Mobile	5.642	2.863	282	242.826	52.437	28.269	944	1.105	7.073	16.343.815
Natural	438	99	N/A	N/A	101	8.734	N/A	0,1	930	N/A
Total	**10.745**	**5.142**	**1.003**	**281.035**	**60.906**	**163.959**	**14.896**	**1.263**	**49.581**	**22.005.070**

Table 1. Contaminant emissions of Mexico City by jurisdiction 2016. Source: translated from Secretary of Environment of City of Mexico. Inventory of emissions of the City of Mexico 2016. General Office of Air Quality Management, Office of Air Quality Programs and Emissions Inventoried. Mexico City, September 2018.

Consequently, Mexico has assumed an international nonconditioned commitment to carry out mitigation actions that will result in a reduction of 22% of its GHG emissions by 2030. The goals established for the energy, industrial, and transport sectors are detailed in Table 2. The emissions mitigation route implies that the current trend of annual emissions increases would gradually change until reaching a maximum around 2026 when net annual emissions would begin to be reduced to reach the goal in 2030 (CDMX, 2015).

Goals in the Energy and Industrial Sectors

- Generate 35% of clean energy in 2024 and 43% by 2030. Clean energy includes renewable sources, efficient cogeneration with natural gas, and thermoelectric plants with CO_2 capture.
- Replace heavy fuels with natural gas, clean energy, and biomass in the economy's industry.
- Reduce by 25% leaks, venting, and controlled burning of methane.
- Control black soot particles in industrial equipment and facilities.

Goals of the Transport Sector

- Standardize in the North American Free Trade Agreement (NAFTA) the environmental regulations for vehicles, both new and in circulation, as well as nonroad vehicles: locomotives, boats, and mobile agricultural and construction machinery.
- Supply of ultra-low sulfur gasoline and diesel.
- Increase the natural gas vehicle fleet and have clean fuels.

–	Modernize the vehicle fleet and reduce the import of used cars.
–	Promote Multimodal Transport of cargo and passengers.

Table 2. Goals of the energy, industrial, and transport sectors in Mexico. Source: Prospective of renewable energies 2012-2026 the United Mexican States.

In addition to the goals included in the commitment to mitigate and adapt to climate change for the 2020-2030 period, both at the federal and state levels, different incentives have been created to accelerate the introduction of electric vehicles in the Mexican market. Mexico has a recognized track record in the automotive industry; therefore, it has the potential to play a leading role in the production and assembly of electric vehicles and their parts. Figure 6 shows the growth in the sale of electric and hybrid vehicles in the local market.

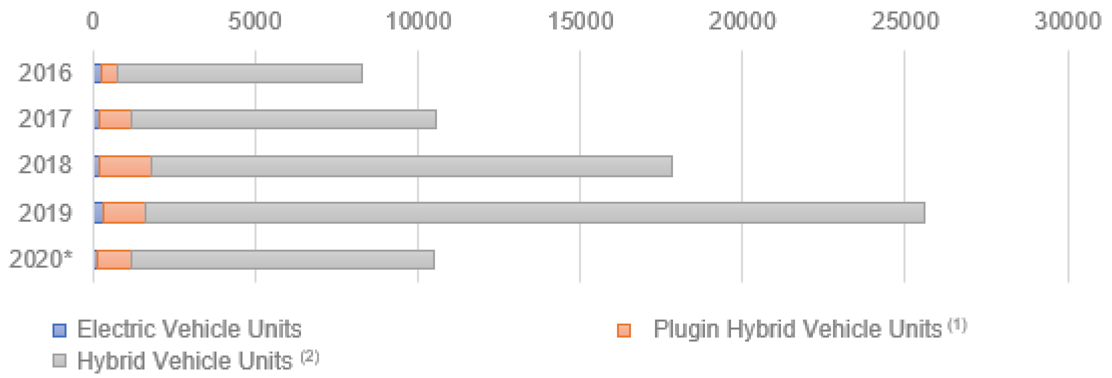

Figure 6. Sale of hybrid and electric vehicles. (*) Data updated to June 2020. (1) Plug-in electric hybrid vehicles mainly use an electric motor that can be recharged by connecting it to the electricity grid. (2) Hybrid electric vehicles that use an electric motor for support and cannot be recharged by connecting them to the electrical network. Own elaboration based on information provided by INEGI.

Both the federal and local governments have established incentives that aim to promote the transition to electric vehicles. For example, at the federal level as of 2015, electric vehicles do not pay the tax on new cars (ISAN) (Congreso México 2006), favoring increased sales (INEGI). Likewise, the Federal Electricity Commission[7] (CFE) has developed a program to place separate meters for chargers in a slow mode of up to 10 kW in the homes of customers with electric vehicles. Enrollment in the program is free, and the user has access to a differentiated electricity rate for charging batteries for electric mobility (CFE 2016).

Likewise, at the state level, the possession tax that is charged annually as a travel permit does not apply to electric vehicles. In Mexico City, electric vehicles are exempt from this charge for the first 5 years and pay a tax reduced by 50% for the next 5 years. In Mexico City as well as in the State of Mexico, electric vehicles are exempt from the "*Today do not travel*[8]" program that establishes measures that limit vehicle flow as well as vehicle verification every semester (SEDEMA 2019). Finally, electric vehicles are expected to have access to an eco-label in the form of an ecological license plate that will entitle the

[7] From Spanish: *Comisión Federal de Electricidad (CFE).*
[8] From Spanish: *Hoy no circula*.

driver to preferential parking reserved for electric mobility, along with other associated benefits.

In March 2016, an initiative was presented to generate additional tax incentives for electric vehicles. At first, these would be exempt from payment of the value-added tax (VAT), among other benefits that would be granted preferentially for vehicles assembled in Mexico. Simultaneously, different initiatives seek to promote the use of electric vehicles, including the cooperation agreement signed between the CFE[9] and the Mexican Association of the Automotive Industry (AMIA), which seeks, among other actions, to develop a charging station development plan, foster dialogue between public and private sector organizations, as well as coordinate and provide information related to the electric and hybrid vehicle market in Mexico (Forbes 2015).

The Public Transport Network in Mexico City

Mexico City, being one of the most populated cities in the world, has a complex, diversified, and extensive public transport network with profuse connections that cover the entire Metropolitan Area of the Valley of Mexico,[10] as can be seen in Figure 7.

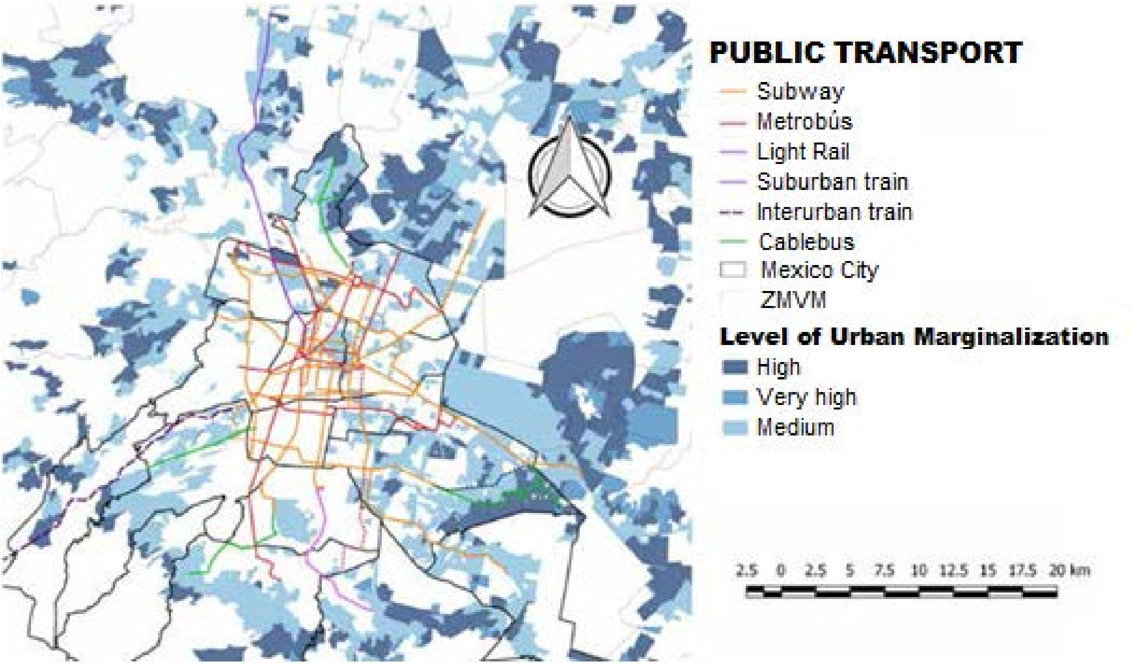

Figure 7. Extension of mass public transport to the periphery and marginalized areas of Mexico City. Own elaboration based on information provided by Government of Mexico City - Source: Strategic Mobility Plan of Mexico City 2019.

Description of Different Public Transport Modes

The public transport network in the city is made up of the following modes, whose trips are distributed as shown in Figure 8:

[9] From Spanish: *Comisión Federal de Electricidad (CFE).*
[10] From Spanish: *Zona Metropolitana del Valle de México (ZMVM).*

- METRO: the mass transport system that supports the entire network with an extension of 226.5 km, 12 lines in operation, 195 stations, and 384 trains (3,333 wagons). It makes 28.7% of the 15.57 million trips in public transport.

- METROBUS: a public entity that manages a BRT network that runs through Mexico City. It has a total of 239 stations, 8 lines (5 trusts and 3 collector companies). Each line has different routes to optimize demand coverage and to connect with other means of public transport (busses, minibuses, trolleybuses, suburban train, and metro) to be able to feed each other.

- STE (Electric Transportation Service[11]): a decentralized public body that is in charge of operating the light rail and trolleybus lines in the city. The trolleybus has an extension of 203.64 km and has 290 trolleybuses divided into 8 lines. The light rail has 16 stations.

- RTP (Passenger Transport Network[12]): a decentralized public body administered by the Government of Mexico City that offers urban bus service on 94 routes and moves an average of 260 thousand passengers per day.

- Microbus or Combi: a concessioned transport system that consists of vehicles smaller than buses. It groups together minibuses, also known as micros or peseras, and combis, which are smaller vehicles. There are 2,311 different routes spanning primary and secondary roads. According to the Ministry of Mobility (SEMOVI), the average number of trips made by minibuses, small buses, and combis is 11.54 million daily.

- Taxi: a form of public transport in the city with a meter and five different rates. According to the Mobility Secretary (SEMOVI), as of September 2019, the total number of taxis was 102.000.

- Ecobici: an individual urban transport system on bicycles operated by a private company that has 480 cycle stations and 6,800 bicycles. It can be used by the payment of a fee that varies depending on the chosen plan (Annual, Temporary 7 days, Temporary 3 days and Temporary 1 day). In 2019, 8.4 million uses were registered (CDMX).

[11] From Spanish: *Servicio de Transporte Eléctricos.*
[12] From Spanish: *Red de Transporte de Pasajeros.*

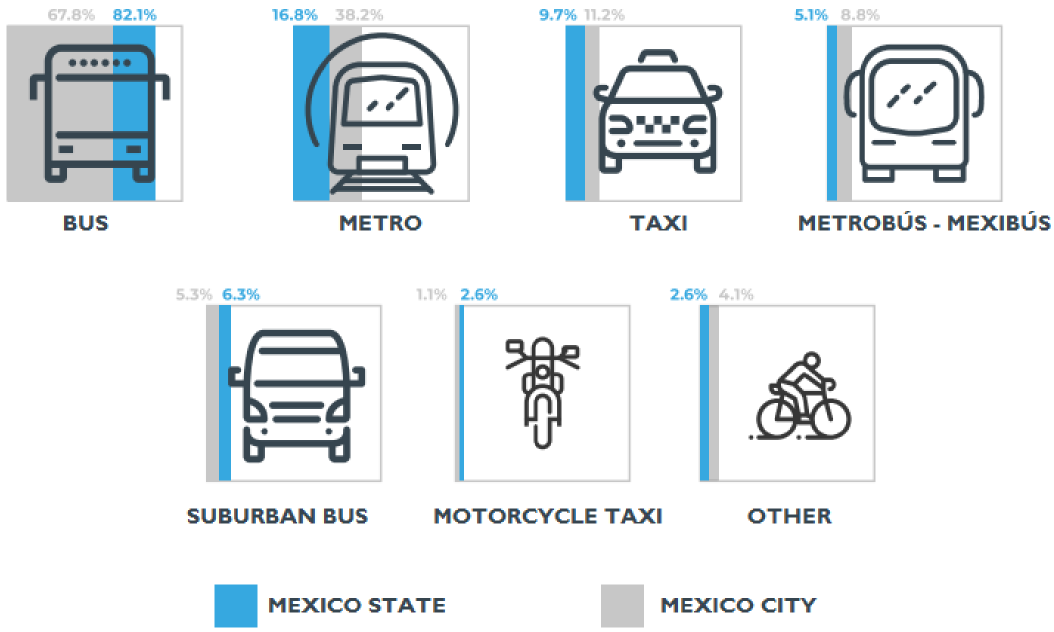

Figure 8. Distribution of public transport trips in the Metropolitan Area of the Valley of Mexico, 2017. Own elaboration based on information provided by INEGI, 2017.

The Metrobus

The Metrobus system has been developed with the help of various national and international institutions, including the Government of the Federal District, the World Bank, the Shell Foundation, and the Center for Sustainable Transportation. This project is part of the Program to Improve Air Quality in the Metropolitan Area of the Valley of Mexico 2002-2010 (PROAIRE), the Local Climate Action Strategy (ELAC), and the Transportation and Roads Plan of Mexico City 2001–2006 (PITV). It is a massive transport alternative, based on the operation of trunk routes with a dedicated infrastructure. It is identified by a higher operating speed when traveling through exclusive lanes segregated from private traffic and special stations, which allows the ascent and descent of passengers to be carried out efficiently using high-platform buses and special fare collection devices.

According to international standards, the Metrobus is defined as a BRT system that is becoming popular as a form of transportation in cities of different latitudes. It is defined as a massive transport system, with a regulated and controlled operation and centralized collection, that operates exclusively in a road with lanes reserved for public transport, totally or partially confined, that has predetermined stops and infrastructure for ascent and drop-off of passengers and stations located along the route and terminals at their origin and destination. The scheme is made up of four fundamental elements:

A. A public body responsible for regulating the service

B. Efficient operating companies that provide transportation service

C. A private administration, distribution, and investment trust

D. A modern fare collection system, for the efficient and transparent management of the income.

The legal and work relationship between all the actors of the system is governed by contracts, agreements, the investment trust, the operating rules, existing regulations, and other instruments defined and endorsed by current laws. Thereby, the system is regulated by a public entity of the government of Mexico City, created by decree on March 9, 2005, and named the Metrobus Decentralized Public Organization (previously referred as Metrobus). Regarding the operation of the system, 25% is done by the surface transportation company of the local government called the Passenger Transport Network (RTP, for the acronym in Spanish) and the other 75% by private companies.

The Metrobus system, whose map is shown in **¡Error! No se encuentra el origen de la referencia.**, is currently made up of seven lines and has an infrastructure of approximately 160 kilometers of confined lanes and 258 stations (15 stations under construction). In 2019, it transported an average of 1,076 million passengers daily (INEGI, 2019),[13] with Line 1 having most absorption of the total system demand per day.

The average age of the buses is 5.4 years,[14] and the fleet is made up of 673 buses with the following characteristics: 9 low-floor hybrids, 61 diesel-powered low-floor units, 90 double-deckers, 401 articulated, and 110 bi-articulated with diesel engine (CDMX). The current operating rules for the BRT concessions establish that vehicles can provide 10 years of service, after which they must be replaced by new vehicles.

The Metrobus vehicle fleet complies with the Official Mexican Standard[15] (NOM) 044-Semarnat. This regulation establishes the maximum permissible emission limits for total hydrocarbons, nonmethane hydrocarbons, carbon monoxide, nitrogen oxides, particles, and smoke opacity from the exhaust of new engines that use diesel as fuel and that will be used for the propulsion of new automobiles with a gross vehicle weight greater than 3.857 kilograms, as well as for new units with a gross vehicle weight greater than 3.857 kilograms equipped with this type of engine. To comply with this standard, the fleet has 33 buses with Euro III, 49 Euro IV, 471 Euro V, 30 Euro V + (particle filter), and 90 Euro VI environmental certifications.

[13] Currently, with the effect of the pandemic, the passengers transported are 750 million. Source: Metrobus 2021.
[14] Average refers to 2020.
[15] From Spanish: *Norma Oficial Mexicana (NOM).*

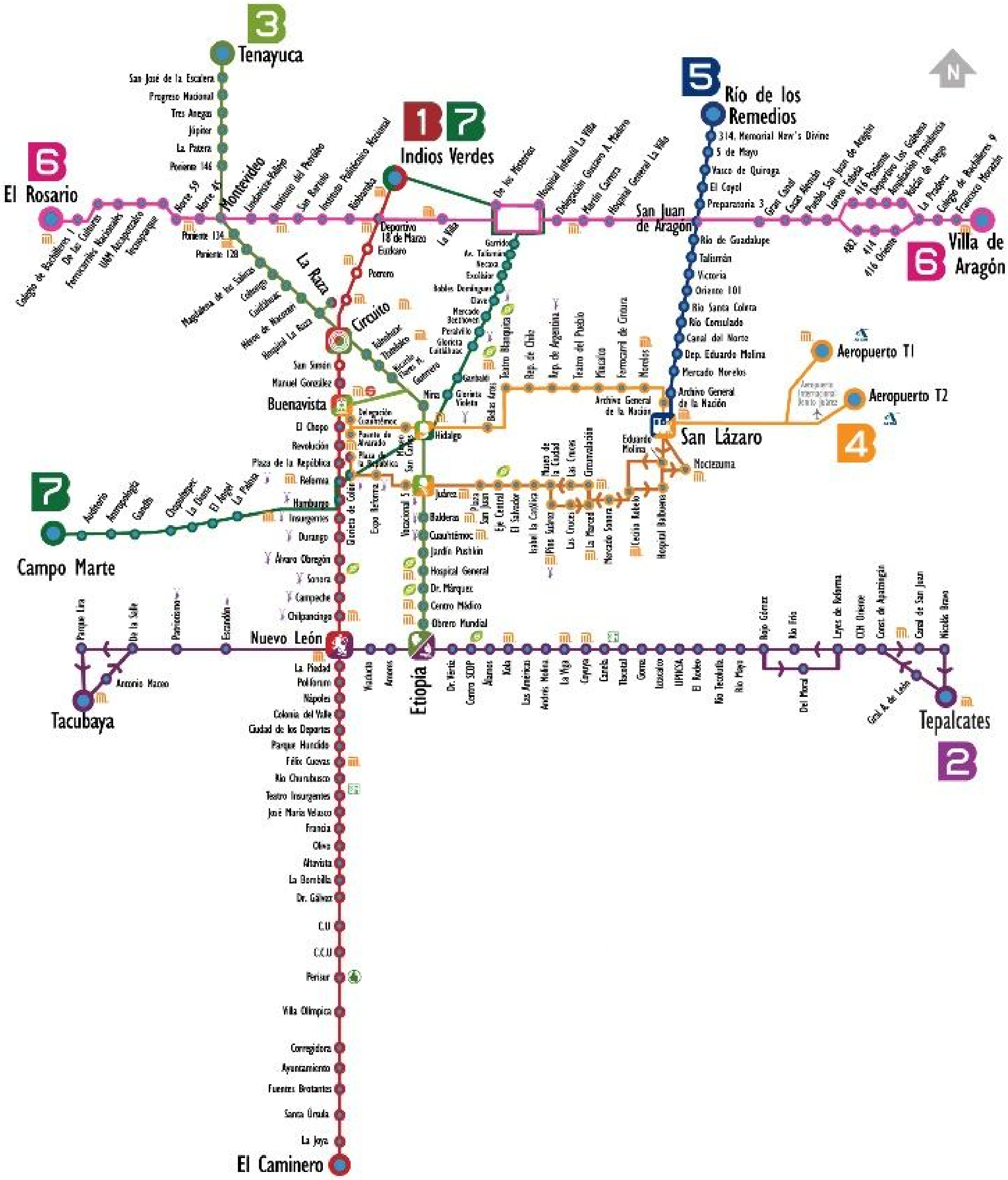

Figure 9. Metrobus Mexico City map. Own elaboration based on information provided by Metrobus - Source: https://www.metrobus.cdmx.gob.mx.

CASE ANALYSIS: Pilot Project to Incorporate Electric Buses Into the Metrobus System

The main objective of this analysis is to document the progress of Mexico City in the implementation of strategies to increase the energy efficiency of the transport sector and to strengthen the mechanisms and institutional coordination between the transport and energy sectors. In this context, the Metrobus entity aims to transition the BRT to cleaner modes. While this BRT system is only one component of the public transportation system in Mexico City, its eventual success has great potential to further accelerate the adoption of zero-emission buses. Thus, here we will discuss the good practices at each step of the planning phase of this pilot project.

The Metrobus entity seeks to transform the public transport system in Mexico City through the electrification of the fleet of BRT lines. Fleet modernization pursues benefits in air quality, reducing greenhouse gas emissions and improving travel times, safety, and user comfort. In this sense, its implementation comprises a progressive step in the direction of sustainable mobility, potentially enabling an effective reduction of GHG emissions based on an articulation of low-emission transport strategies and the efficiency of the energy matrix.

To progressively execute a fleet transition to electrification, with the eventual goal of complete substitution of the whole current bus fleet made of ICE vehicles, Metrobus put in motion a pilot phase with a series of stepwise considerations that take into account key aspects of the decision-making process. In this manner, the approach within each step articulates key criteria and good practices and will enable additional scale-up phases of the electrification interventions in all lines of the BRT system. The steps of the first pilot phase are conceptualized into four key steps and shown below.

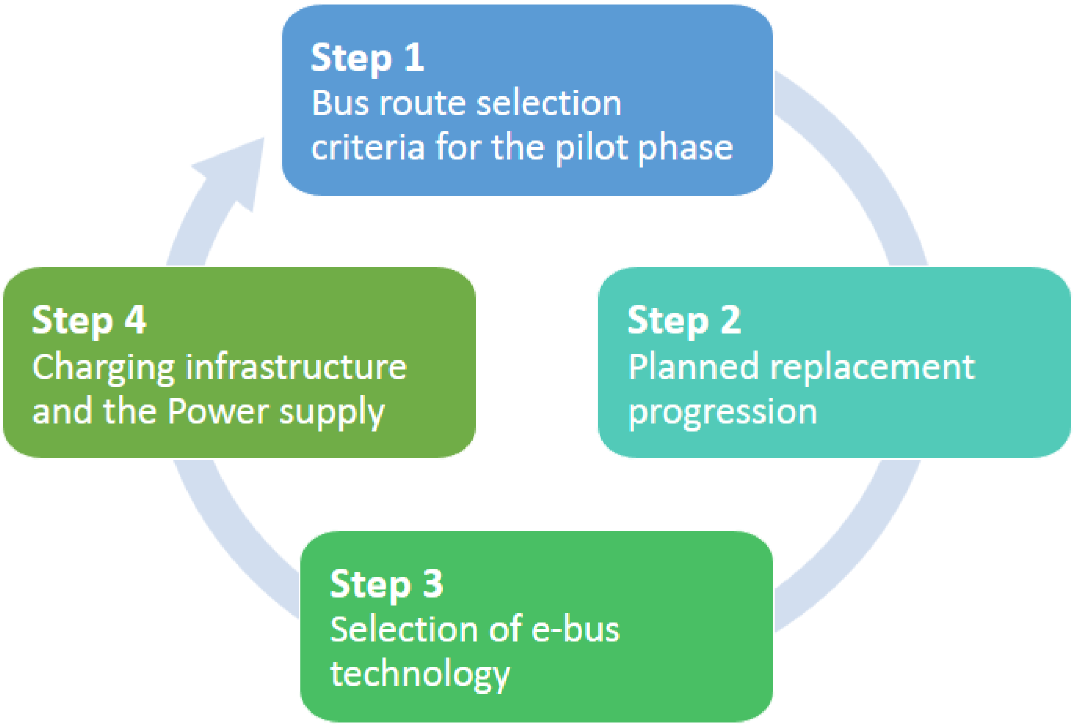

Figure 10. Steps for the development of the pilot phase project. Own elaboration.

Step 1. Bus Route Selection Criteria for the Pilot Phase

The first step that Metrobus carried out was the selection of the bus route, also known as the Line, which would be the focus of the pilot project for electrification and modernization of the system. This choice required a dialogue and collaboration that took more than a year between the authorities of Mexico City, Metrobus, ENGIE (energy and services company), the concession company, and MOBILITY ADO[16] acting as an advisor.

To select a Line, it was necessary to conduct an analysis of the BRT-type transport corridors that have ongoing implementation programs (planning of extensions, fleet renewals, etc.). Also needed were studies of supply and demand of public passenger transport within each Line and operational indicators. As we have previously mentioned, the BRT system is made up of 7 Lines with a total of 673 buses in operation, whose distribution can be seen in Figure 11.

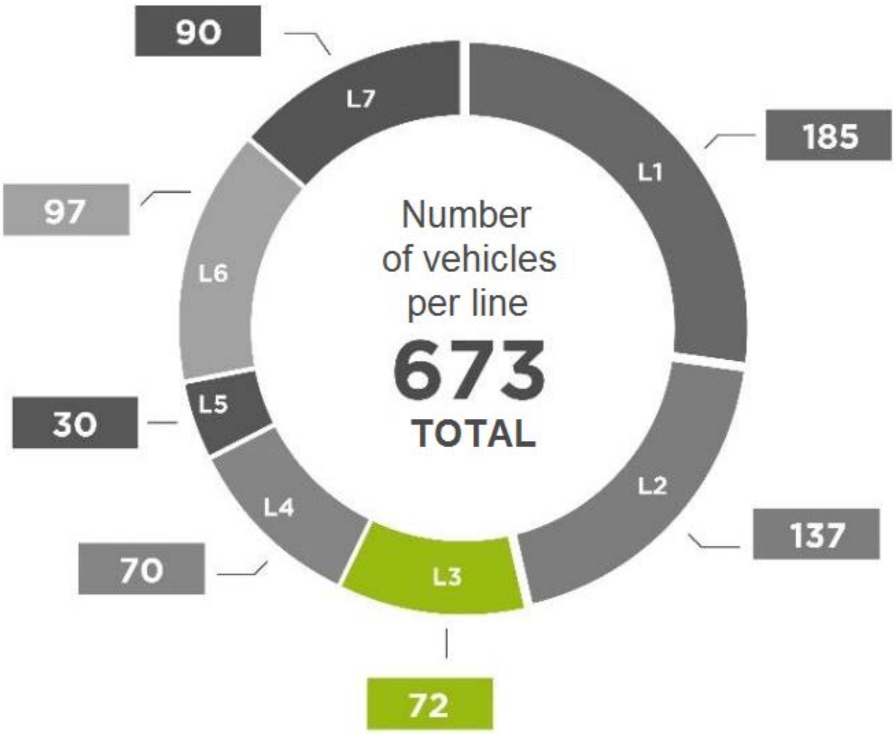

Figure 11. Number of buses in the Metrobus 2020 fleet lines. Own elaboration based on information provided by Government of Mexico City.

The considerations of all involved actors and their analyses led to identification of an opportunity to implement the pilot project on Line 3, which has 72 buses in operation and runs along the corridor *Eje 1 Poniente*. At present, Line 3 has a 4.27-km extension plan, and its development, according to the latest population and housing survey carried out by INEGI, would benefit a user population of approximately 95,000 inhabitants. Additionally, according to Metrobus, it is the second line in terms of volume of passengers transported per kilometer traveled, following Line 1.

[16] MOBILITY ADO is a company that provides quality urban mobility services, with the aim of providing innovative, sustainable solutions adapted to your specific mobility needs. Source: https://www.mobilityado.com/.

Figure 12. Metrobus Line 3 map. Source: http://data.metrobus.cdmx.gob.mx/fichas.html#tres.

The Eje 1 Poniente's fleet is operated by a single concession company that currently provides its services through 72 diesel units (Figure 11), each one 18 meters long and with a capacity for 160 passengers. Line 3, whose map can be seen in Figure 12, operates in a time slot between 04:30 and 24:00 on four routes of different lengths: (1) Tenayuca–Ethiopia of 17.0 km; (2) Tenayuca–Buenavista II of 11.5 km; (3) Tenayuca–La Raza of 8.8 km; and (4) Tenayuca–Balderas of 13.2 km.

In a regular week, the service of Line 3 fleet, which has 72 diesel buses, comprises the functioning of 46 buses on Mondays, 71 buses between Tuesdays and Fridays, 52 buses on Saturdays, and 39 on Sundays. All buses travel an average of *6.1 million kilometers per year*, making up for an average of *330 kilometers per day without the need to refuel*. Line 3 offered the advantage of being operated by a single concession company, which facilitates an efficient planning and implementation process of the fleet replacement stages in the transition towards the adoption of electric buses.

The ***good practice from Step 1*** that is worth replicating is deciding the factors that lead to the selection of a bus route to implement a pilot phase. In this case study, a *high volume of current and future passengers and an existing planned route extension made Line 3 a good candidate for the implementation of a first pilot for the electrification process of a BRT corridor.*

Step 2. Planned Replacement Progression

The next question that came up in the design of this pilot project was how many electric buses to add to the selected route. The Line 3 bus fleet has been in service for approximately 7.75 years, which is well above the average for the total Metrobus fleet. The characteristics of the 72 units that currently function in Line 3 are shown in Table 3. Of those 72 units in operation, 54 of them end their period of service in 2021 and must be replaced based on the current operational rules of the BRT's concessions.

CONCESIONARY	BUS MODEL	FLEET	BUS TYPE	DATE OF ENTRY INTO OPERATION	TECNOLOGY	SERVICE YEARS
MIVSA	MERCEDES BENZ GRAN VIALE	**54**	ARTICULATED	2011	EURO V	9
	MERCEDES BENZ GRAN VIALE	**6**	ARTICULATED	2012	EURO V	8
	MERCEDES BENZ GRAN VIALE	**6**	ARTICULATED	2017	EURO V	3
	MERCEDES BENZ GRAN VIALE	**6**	ARTICULATED	2019	EURO V	1
TOTAL		**72**				

Table 3. Line 3 fleet vehicles' characteristics. Own elaboration based on information provided by Metrobus 2021.

As replacement buses are soon needed in Line 3, this pilot project aims to deploy in its first stage a total of 10 new electric units by 2021. Based on the resulting experience over a period of 1 to 2 years, plans to implement the following stages that will allow progressive replacement of all ICE buses will be defined.

The number of the initial 10 units was defined based on a scheduled fleet expansion of Line 3, which was considered necessary in the context prior to the 2020 pandemic in relation to the supply and demand of passengers on the line. Subsequent to the 10 initial electric buses, the number of units in the next stages will be defined based on the scheduled renewal process that Metrobus had already developed that is part of the operating and concession conditions. Therefore, the pilot implementation stages correspond to an initial stage of 10 buses, a second stage of 54 units whose service period ends in 2022, and subsequent stages to be defined for the remaining 18 buses, as shown in Figure 13.

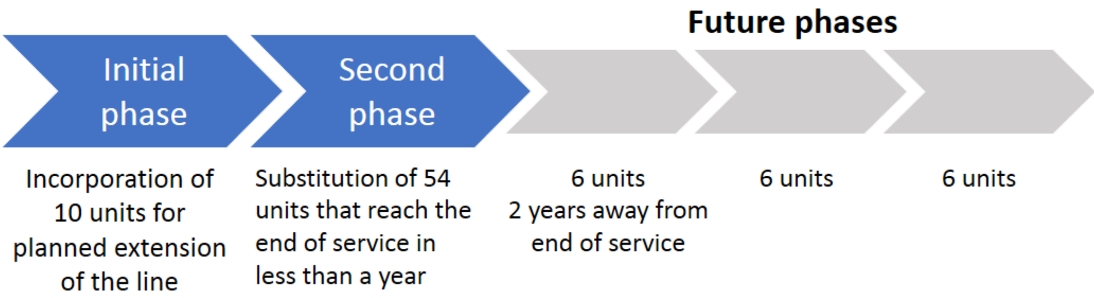

Figure 13. Implementation phases of the pilot project according to the number of electric units to be deployed. Own elaboration.

The ***good practice from Step 2*** that is worth replicating is *deciding the progression by which the fleet transition will occur over time to eventually result in a complete e-bus fleet*. In this case analysis, Metrobus decided it was best to follow the already existing replacement timeline of the fleet in Line 3 for the ICE buses, and therefore the costs are expected, planning is staggered, and redundancy is minimized. The staggered progression also enables the fleet managers to learn from each addition, with data, costs, and maintenance, and thus enabling even more scale-up by sharing these with others within Metrobus.

Step 3. Selection of E-Bus Technology

The Zero Emission Bus Rapid-deployment Accelerator (ZEBRA) team in Mexico collaborated with Metrobus by providing technical support to determine the technical characteristics of the most suitable electric buses for the Metrobus BRT system. The purpose of the analysis and advice was to evaluate the minimum technical requirements necessary to ensure proper operation throughout the entire useful life of the vehicles under normal BRT operating conditions (Figure 14).

Figure 14. Metrobus electric buses. Source: Metrobus 2021.

The first requirement was that the e-bus should be able to travel a minimum distance of 330 km without needing to recharge to keep Line 3's operational conditions similar to current conditions. Secondly, it was also determined that the maximum allowable annual battery degradation rate should be limited to 20%. These main parameters were necessary for maintaining a minimum and optimal battery load capacity of 75% throughout the 10 years of operation required by the operation and concession rules. The analysis of the necessary operational requirements carried out by the ZEBRA team concluded that the most suitable vehicles for the Mexico City Metrobus system are buses with an electric propulsion system powered by a battery system (battery electric buses, BEB) with regenerative braking systems and other electric components.

Electric buses bring a series of advantages and benefits compared to the operation of ICE buses. According to Metrobus (METROBUS 2020), in relation to the diesel buses in the current fleet, the previously stated chosen BEB units reduce the cost of energy (i.e., cost of diesel compared to cost of electricity) use by 80% and also avoid, in 10 years of operation, the emission of 300 thousand tons of CO_2 equivalent.[17] Therefore, they contribute to improving air quality by eliminating 14 tons of local pollutants in the same time period, including particulate matter, harmful to the respiratory system, and nitrogen oxides, associated with ozone contingencies.

The main advantages of the use of electric buses versus internal combustion engine buses can be summarized into four key points:

First, the costs of electricity consumption per km traveled are usually lower than the equivalent cost of diesel consumption, which means that electric buses run on a more economical source of energy.

Second, as recognized by Metrobus, electric buses have no tailpipe emissions or particulate matter, leading to a reduction in local pollution in highly dense urban cities. Additionally, they do not generate noise, improving the quality of the urban environment.

Third, the energy efficiency of a combustion engine is lower than that of electric motors, as combustion generates a lot of unusable heat and requires many moving parts that generate losses through friction.

The *fourth* advantage is that the maintenance costs of electric buses are comparatively lower. This is because they are less complex systems and do not require the use of lubricants for mechanical moving parts. These four factors affirm that incorporating electric bus fleets can have economic advantages and can contribute to the rapid decarbonization of the transport sector, as well.

However, it must be considered that a transition to a completely electric bus system implies a significant capital investment cost for the acquisition of the vehicles and the implementation of a charging infrastructure integrated into the local energy distribution system. In addition to understanding the basics of planning for the transition, these aspects are usually the main barriers to a scaled-up implementation of electric buses.

The ***good practice of Step 3*** that is worth replicating is deciding the *type of electric bus that best suits the public transport system and the operation of the service*. In this case analysis, Metrobus selected buses with a range of 330 km powered by a high-capacity battery system. This type of technology allows the current operation of the system to be kept unaltered without having to adapt the road infrastructure.

[17] Referring to tailpipe emissions.

Step 4. Charging Infrastructure and the Power Supply

At present, there are two possible alternatives for the charging infrastructure for the electric buses. The *first* is with the use of large-capacity batteries on the buses, that are recharged at the terminal station, typically lithium ferrophosphate (LFP). The *second* is an opportunity charge using small, very fast-charging batteries, which must be recharged frequently during the day. Both recharging technologies also have different operational implications and infrastructure requirements. Above all, the opportunity charge allows continuous operation during the day, but the bus needs frequent recharges, which requires a precise design of the service to avoid interference in the operation.

Considering the operating characteristics of the Metrobus system and the analysis of the ZEBRA equipment mentioned previously, a deep recharge system at the terminal station was chosen (*first option*), which is the first option of charging associated with large-capacity batteries (Figure 15). This system allows electric vehicles to operate for a full day from a deep charge carried out at night through stationary charging systems. This is convenient because Line 3 operates in a time slot between 04:30 and 24:00, allowing the recharging phase of electric vehicles exclusively in the nighttime slot from 24:00 to 04:30.

Figure 15. Electric charging station and technical characteristics. Source: Metrobus 2021.

Based on the analysis and considerations mentioned above, deep charging will take place in the terminal yard of Line 3[18]. The terminal will have to provide a recharging system suitable for buses with a battery pack of more than 500 kWh. This capacity will allow the vehicles sufficient autonomy for daily operation with a discharge percentage of 70%, as well as guaranteeing a residual capacity above 80% of the nominal capacity for the entire useful life of the batteries. Charging is slow and it will take between 4 and 5 hours for a bus to be operational again. This type of technology allows not to affect the current operation of the line, but for that same reason it is constraint to the charging capacity during the night charging period.

[18] The terminal yard of Metrobus line 3 is located near the Jupiter station and has an area of 12,000 mq.

The ***good practice from Step 4*** that is worth replicating is *implementing a technical analysis of the range and operational requirements of the selected bus route, considering the operational and refueling costs, and finally, selecting the spatial layout of the charging infrastructure that enables optimum operation in accordance with the existing agreements and contracts*.

Moving From Planning to Implementation and Scale-Up Criteria

Currently, the Metrobus system electrification project is in a development phase and operates with a single electric bus on Line 3 (Tenayuca-Ethiopia) since September 25, 2020, which has had good acceptance by users. Metrobus is preparing the launch of the next nine buses. It is expected that in the coming months, at the start of 2021, the operation of the 10 incorporated buses will be monitored, and the plan for the next stage of project deployment will be planned in detail.

Comparative Analysis of Energy Consumption and Costs (Diesel/Electric)

The operation in a regular week of the Line 3 fleet, constituted as previously mentioned by 72 diesel buses, contemplates the use of 46 buses on Mondays, 71 buses between Tuesdays and Fridays, 52 buses on Saturdays, and 39 Sundays. Though the actual value varies depending on the branch (Tenayuca–Etiopía, Tenayuca–Buenavista II, Tenayuca–La Raza, Tenayuca–Balderas), all buses travel an average of 6.1 million[19] kilometers per year, corresponding to 330 kilometers per day without the need to fueling.

A background study conducted by NREL in collaboration with the United States Agency for International Development (USAID) in 2017 evaluated the potential for electrification using speed data obtained with GPS from transit buses in Mexico City and two other Mexican cities. Figure 16 shows the estimated energy consumption based on the number of passengers transported, as well as the savings in diesel fuel and the reduction in GHG emissions.

Considering the current characteristics of the Line 3 and the previous studies (*Transit Bus Electrification Evaluation from GPS Speed Traces, 2017*), operating costs[20] were analyzed and estimated in different future scenarios of incorporation of electric buses. Table 4 shows the results obtained when calculating the consumption and energy costs of the diesel buses of the current operation and the selected BEB, having considered the average daily travel distance or autonomy distance established as a minimum requirement of 330 km.

[19] Referring to the kilometers traveled on Line 3 in 2019 (CDMX).
[20] Exchange Dollar-Mexican Peso (21/08/2020), $1 US = $21,176 (Secretaria de Gobernación [SEGOB]).

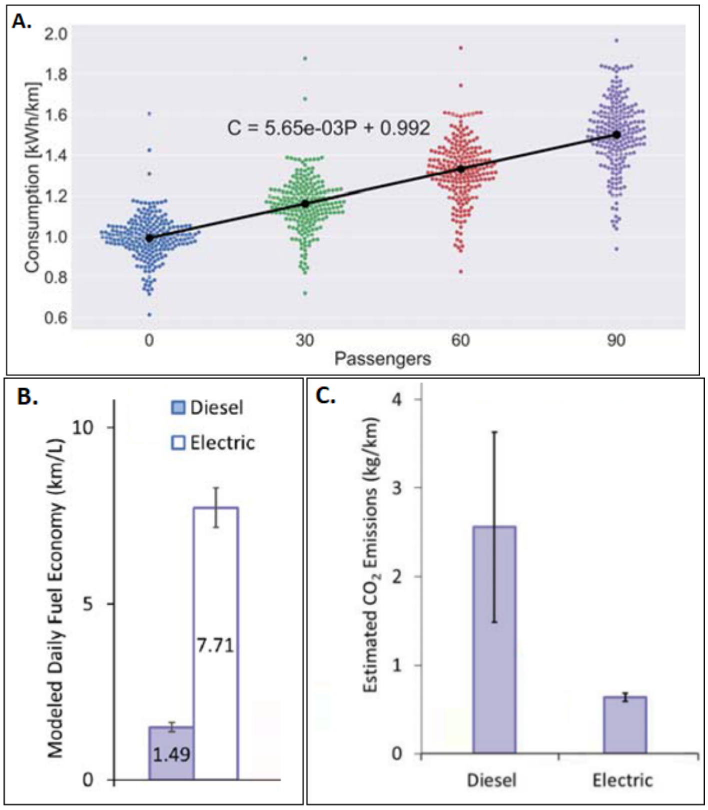

Figure 16. A. BEB energy consumption based on the number of passengers. B. Average Daily Fuel Savings for Diesel and Electric Buses. C. Combined CO_2 emissions for diesel and electric buses. Source: Transit Bus Electrification Evaluation - USAID-NREL, 2017.

Number of buses	km/day	Diesel Bus		Electric Bus		Δ[21]
		Consumption [l][22]	Cost [US$/l][23]	Consumption [kWh][24]	Cost [US$/kWh][25]	[US$/year]
1	330	221	241	350	101	50.938
10	3.300	2.211	2.410	3.498	1.014	509.383
54	17.820	11.939	13.014	18.889	5.478	2.750.668
60	19.800	13.266	14.460	20.988	6.087	3.056.298
72	23.760	15.919	17.352	25.186	7.304	3.667.558
82	27.060	-	-	28.684	8.318	

Table 4. Estimation of the daily operating costs of Line 3 comparing current buses and electric buses. .

Likewise, it has been possible to estimate a significant reduction in the pollutants generated in the city, the results of which are shown in Figure 17. According to the Metrobus records (2016) prior to the 2020 pandemic, the Metrobus system emitted 143,952 tons of CO_2 per year and 24,445 of the total were generated by Line 3. With the replacement of the entire Line 3 fleet of internal combustion buses by electric buses, tail

[21] Difference between the costs of fuel and energy relative to a year of operation.

[22] It is considered a fuel consumption of 0,67 lt/km (USAID-NREL, 2017).

[23] Average diesel price on 21/08/2020, US $1.09 (CDMX).

[24] This value is highly dependent on the driving habits of the operators; it is necessary to know this value to make the most accurate estimates of consumption. This information allows us to know the autonomy of the vehicle; that is, the number of kilometers that the vehicle can travel without the need for refueling. Metrobus has measured this value to 1.06 km/kWh.

[25] A cost of $0.29 US per industrial kWh of the medium-sized company sector with medium voltage installation was considered. (Sistema de información energética [SIE]).

pipe CO_2 emissions could be reduced by 17%[26] of the total of the emissions from the Metrobus system. The significant reduction of pollutants emitted in the city center translates into a positive impact on the health of the population, improving their quality of life, survival, and control of chronic diseases (INER, Mexico City).

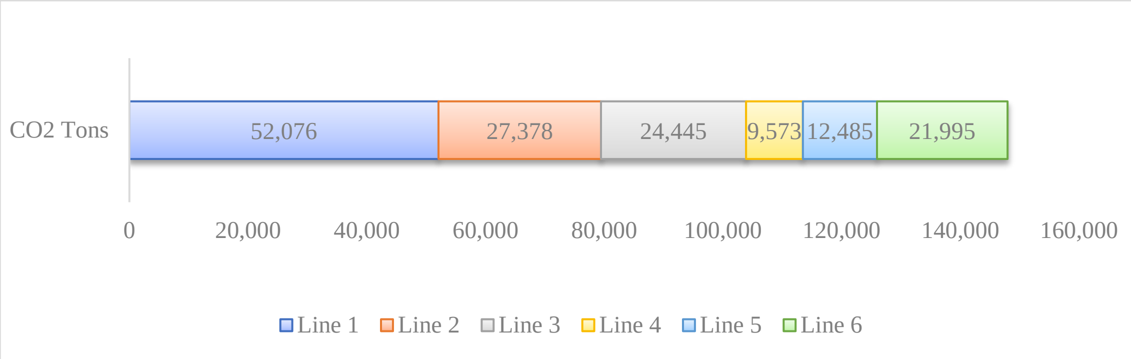

Figure 17. Reduction of the tons of CO_2 emitted by the Metrobus 2016 system. Calculations are made under the criteria of the NM0258 methodology. Own elaboration based on information provided by https://www.metrobus.cdmx.gob.mx/.

Additional Considerations Regarding the Renewal of Line 3

The pilot project has a high capital cost required for the initial investment in the acquisition of the 10 electric buses[27] and a moderate capital cost required for the recharging infrastructure. However, the implementation of electric buses immediately shows the main advantages of the implementation of this stage by significantly reducing fuel costs (energy) compared to the acquisition of new diesel buses, as can be seen from Table 4.

The choice to incorporate 10 electric buses instead of internal combustion buses can generate economic savings of approximately $500,000 U.S. per year. These savings may be even greater if we consider that the cost of electricity has remained stable in recent years and the value of diesel is partly subsidized, a subsidy that could be reduced in the future or whose price may vary strongly due to fluctuations in the international oil market. Even in a hypothetical scenario with heavily subsidized diesel, given the high energy efficiency of electric motors compared to traditional heat engines, electric buses still result advantageous in terms of consumption.

Adding to the energy costs, diesel buses require high-cost components that the electric system does not, and those differences should be considered. For example, fuel and lubricating oil supply stations in garages or terminals are necessary infrastructures for the operation of internal combustion buses (OPEL, 2020). These infrastructures are replaced by charging and maintenance stations whose operation and management are simpler.

However, it can be said that the dimensions of the terminal and maintenance yards are independent of the technology used for the vehicles. Although electric buses do not require areas for supplying fuel or lubricants, it is necessary to dedicate comparable areas for recharging systems. In this sense, it can be considered that there is no need

[26] This percentage considers only the reduction of pollutants emitted by the tailpipe.
[27] One of the highest costs of electric buses is in high-capacity batteries.

for extra space in the patios, and therefore existing infrastructures can be reconfigured to accommodate the needs of new and future electric buses without the need for extensions to maintain the size of the fleet.

Finally, it is necessary to consider the feasibility of supplying electrical energy and the impact that the energy requirements of the operation of electric buses may have on the electricity supply and distribution system of Mexico City. In this initial instance, the ENGIE company studied the capacity of the system and assured the system's sufficiency to sustain the installation of 6 charging[28] stations with 150 kW capacity. The initial stage of incorporation of 10 buses does not constitute an energy demand problem due to the limited number of electric buses in operation. Additionally, the recharge times are at night times when electrical loads on the grid are minimal compared to day time.

On the other hand, even when the recharge period coincides with a low energy demand in the energy distribution grid (Figure 18), the complete replacement of the fleet with electric buses could weigh heavily on the energy supply system. The fleet of 82 electric buses for Line 3 will have an energy consumption of 28.684 kWh. The type of operation and the frequencies of the line imply few useful hours for the contemporary recharge of the fleet and this could increase the maximum demand in the network, which can contribute to overload and the need for updates at the distribution level.

From an energy perspective, a possible further improvement of the system could be implemented by incorporating a small photovoltaic electric power production plant in the yard with an energy storage system. For the particular case of Line 3, at the Jupiter yard selected for the incorporation of recharging stations (according to the feasibility granted by the energy distribution company, ENGIE) there is potential for the installation of photovoltaic panels with a storage system that must be studied in detail.

Considering the 12,000 square meter area of the yard and the Distributed Solar Generation[29] (GSD) law, one could think of using the area of the bus recharging areas with two sets of photovoltaic panels of 2,000 square meters each (Figure 18). Taking into account that standard photovoltaic panels have an input power of approximately 1,000 W per square meter and an efficiency of 20%, the total installed power in the yard could reach up to 800 kW[30] and contribute significantly to the recharging system and the electrical power distribution system.

[28] A charger can deliver up to 150 kW in a single connector or divide the power into 2 connectors for 75 kW each. Two 150-kW connectors from two different chargers would be used to power the buses at 300 kW.

[29] From Spanish: *Generación Solar Distribuida (GSD).*

[30] Approximate value.

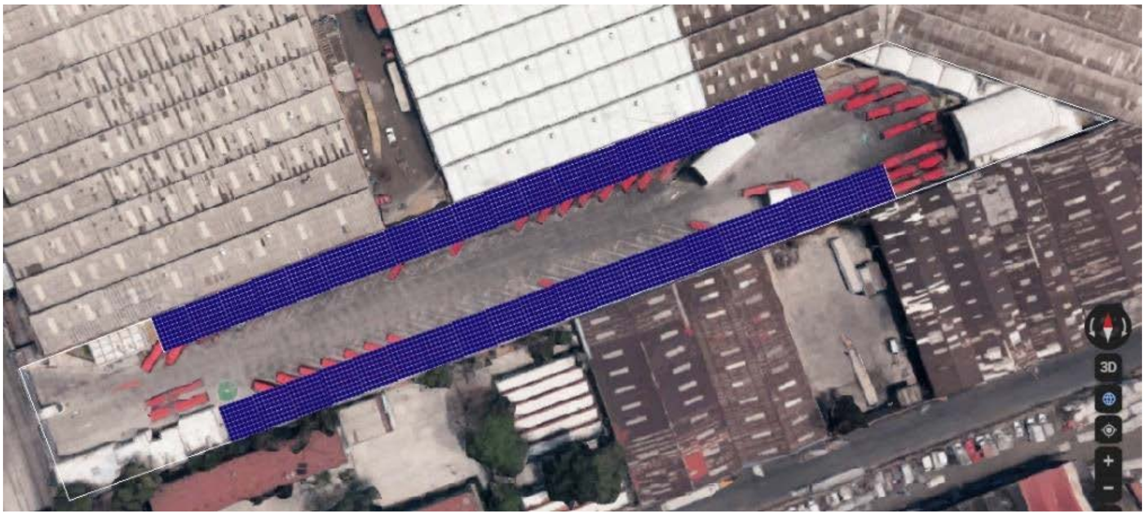

Figure 18. Jupiter patio scheme with the implementation of a photovoltaic plant. Own elaboration based on information provided by Google Maps.

The implementation of a project of these characteristics would be framed under the distributed generation plan in Mexico defined in the Electricity Industry Law as self-supply or exempt renewable energies. Under these categories, the installed capacity of the generation plant must be less than 500 kW and it must be interconnected to a distribution circuit that contains a high concentration of load centers. The Energy Transition Law indicates that if the generation is carried out from clean energies, it is distributed clean generation.

CONCLUSIONS AND RECOMMENDATIONS

Energy demand due to population growth, the increase in comfort standards of modern life, and the intensification of mobility patterns continues to grow, imposing a surprising rate of search for new technologies. Among the possible solutions, the energy efficiency aspects of the energy and transport sectors are emerging with increasing intensity. Therefore, measures with a low relative implementation cost such as the electrification of mass transit systems like BRT allow interesting decreases in the level of fossil fuel consumption and CO_2 emissions in urban areas.

The experience carried out by Metrobus in Mexico City, although at an early stage of planning and implementation, allows us to gather a series of lessons and opportunities to consider, not only in the process of scaling up its electrification project to achieve the vision of completely transforming the public transport system to low- or zero-emission electric vehicles, but also for other cities or urban transit systems.

This Metrobus case study analysis shows that the electrification projects of mass passenger transport systems that are currently in operation have few opportune moments to introduce electric buses into operation. The ***first lesson*** is the importance of deciding on which factors should lead to the selection of a bus route to implement a pilot phase. In the case of Metrobus, after extensive conversations with the relevant stakeholders, it was decided to move forward with a line, the majority of which was to be replaced in the next year, and which allowed the greatest benefits in relation to the expected future volume of trips and passengers. Taking advantage of an operational requirement, it will also be possible to achieve high visibility of the project results, thus obtaining greater acceptance and involvement of the stakeholders to enable future stages of the electrification project.

It worth mentioning that, to choose the scale and scope of the pilot stage, it is convenient to work with a single line or segment of the system that is operated by a single concession company. In this way, conversations can be made more effective by eliminating variability and complexity due to the particularities of different operators. Therefore, the design and implementation of the pilot is facilitated by arriving at concrete operational decisions and allowing a faster and more effective deployment of technologies and infrastructures. In this way, the pilot has a demonstrative effect to initiate conversations with other operators when seeking to address other lines and corridors in future stages of the project.

It worth noting that the planning of the pilot takes place as a joint effort with the city's electric power distribution company, ENGIE. In this case, it was the energy company that took the leadership and responsibility of making the initial investment for the acquisition of the first electric buses and of deploying the recharging infrastructure in the selected site to carry out the electrification pilot stage. ENGIE carried out the analyses to assess the feasibility of supplying energy for the recharging system of the first electric buses, and it must guarantee that the distribution of energy in the city is not put at risk by assuring the capability of energy provision for the installation of new charging stations when implementing future stages of the project.

The ***second lesson*** is to work upfront on *the progression by which the fleet transition will occur over time to eventually result in a complete e-bus fleet*. The number of units to be incorporated was determined based on a scheduled fleet expansion of Line 3. The acquisition of 10 electric buses by the local energy company has such a scale that it allows the rapid deployment of the charging infrastructure also provided by them. Likewise, the 10-unit pilot can provide enough information on the actual operating parameters (versus the design parameters) to allow planning and designing the way in which the next 54 buses corresponding to the replacement plan will be incorporated by 2021.

The selection of the type of electric buses and the recharging system (deep slow charging) was fundamentally associated with, on the one hand, the need to provide autonomy of 330 km per day, the average distance traveled by the buses of Line 3 in all its branches, and, on the other, the time slot available for charging during the night at out of service hours of the Line 3 corridor. The ***third lesson*** of this case study is that the *type of electric bus to be adopted should be the one that best suits the public transport system and the operation of the service*. In this line, the ***fourth lesson*** is that *implementing a technical analysis of the range and operational requirements of the selected bus route, considering the operational and refueling costs, and finally, selecting the spatial layout of the charging infrastructure enables optimum operation in accordance with the existing agreements and contracts*.

At this point, Metrobus prioritized keeping unaltered the operating conditions, such as the frequency and timetable of the branches, avoiding introducing changes in service hours that could affect users of the BRT corridor. This decision has an advantage in relation to the reliability of the service but could have significant impacts regarding the energy requirements during recharging in the scenario in which all buses are recharged simultaneously during the night.

It is well-documented and recognized that electric buses can provide broad benefits compared to traditional combustion buses currently in operation. The estimates made in this study are consistent with other cited sources of information that show that the selected BEB will produce significant savings in energy costs and a reduction in GHG emissions. In addition, there will be savings in maintenance and operating costs related to less complex mechanics (without moving mechanical parts that are subject to wear and without the need for the use of lubricants).

A strategy aiming to implement electric buses plays a fundamental role in reducing emissions and average energy consumption on Line 3. This intervention will allow a saving of 90,000 liters per year of diesel for each vehicle in operation (substituted vehicle), reducing dependence on the use of fossil fuel. Likewise, it will produce a reduction of up to 90% of pollutant emissions, even considering the average emissions generated in the production of electrical energy from the National Interconnected System, thus contributing to both the air quality and health of the population of the urban area of Mexico City and the fight against climate change.

The limitations of the case lie in two issues of technical feasibility: the energy requirements for recharging the new electric buses, and the infrastructure and space requirements of said recharging stations. To implement the recharging infrastructure, a strategic and clear deployment plan must be developed that considers the way in which the infrastructure will be implemented, the initial investment cost, as well as maintenance costs and the operation scheme in relation to the incorporation of fleets.

On the one hand, this case study shows how the energy consumption of a public transport system is directly related to the supply of the service, especially when it is intended to provide the service with autonomy for a whole day of operation. In other words, energy consumption depends on the size of the electric fleet to be deployed. This implies that the recharging system must be carefully planned, verifying the energy demand of the entire fleet in service associated with each yard. According to the estimates presented in this study, a fleet of 82 electric buses for Line 3 will have a consumption of 28.684 kWh, energy that must be provided between 24:00 and 4:30. Although the recharging period coincides with the low demand for energy at night, it is necessary to study in greater detail the energy feasibility for the scenario of recharging all electric buses simultaneously to ensure that the local distribution network is overloaded.

On the other hand, there are space requirements to install the recharging systems. In the case of Line 3 in which the Jupiter yard has been selected for the provision of the bus charging stations, the space and configuration of the yard is enough and adequate for the deployment of the required electrical infrastructure. However, this may not be the case for other lines or corridors where the patios and garages do not allow reconfigurations to accommodate the charging stations for the simultaneous recharging of the entire fleet associated with said yard.

This condition raises a question regarding the efficiency of the use of the available space, as well as the infrastructure and associated investment. For an electric bus charging center, if the charging of the entire fleet takes place simultaneously, the charging infrastructure is not at use during the periods when the fleet is in service. Considering installation criteria for charging and the city's daytime energy consumption curves, the charging center could be planned to function also as a charging station for private user vehicles or other compatible electric vehicles. This would allow consideration of service and business schemes that, by evaluating differentiated energy prices according to the type of user, could make the investment attractive by optimizing capital costs in infrastructure and contributing to the transition towards sustainable urban mobility.

Additionally, the energy requirement for recharging the buses could be met, at least partially, using decentralized photovoltaic panel arrangements installed in the patios of the BRT corridors. Solar generation needs a specific infrastructure for the conversion and storage of electrical energy that is produced during the day so that it can be used for recharging of buses at night. This initiative must be properly designed and adjusted to the requirements and standards of the applicable distributed energy production laws, as well as the energy losses between the generation and storage systems, and the useful life of the batteries necessary for said operation.

The electrification of Line 3 is an integral part of the commitment that the region has to implement mitigation actions on GHG emissions. The energy efficiency that new bus technologies make it possible to achieve in relation to energy consumption per kilometer traveled (kWh/km) can allow a better use of the installed electrical infrastructure capacity and energy resources. In addition, the low speeds and frequent stops that characterize the Metrobus lines, which are common to other dense and congested cities around the world, make them particularly conducive to electrification.

With regard to the Metrobus BRT system, it is advisable to develop a systemic vision of transport services and associated electrical services, that is to say, of the bus fleets with their recharging infrastructures, to achieve substantial improvements in energy efficiency and in the reduction of emissions from the transport sector. Without a doubt, projects of these characteristics are an ambitious and necessary measure that contributes directly to achieving these objectives of transport decarbonization and pollution reduction, while they also help to strengthen institutional coordination mechanisms between the actors of the transport and energy sectors.

Mexico City can obtain numerous environmental, social, and economic benefits with a successful integration of electric buses, renewable energies, and electrical grids. However, to achieve a true decarbonization of transport sector through the complete electrification of the Metrobus system, the generation of energy from renewable sources must be promoted. This experience brings several opportunities to continue developing plans for the deployment of electric mobility in mass passenger transport systems in urban areas, highlighting the need for integrated approaches in the planning and design processes of electrification strategies in the transport sector.

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