Transforming the BRT system for a greener future

Santiago Martínez Paulina
paulina.sam@comunidad.unam.mx

Hernández Albarrán Emma Laura
laura.h.albarran@comunidad.unam.mx

García-Cerrud Carmen Angelina
carmen.garcia@ingenieria.unam.edu

Soler Anguiano Francisca
francisca.soler@ingeniería.unam.mx

Flores De La Mota Idalia
Faculty of Engineering, UNAM
Mexico City, Mexico
idalia@unam.mx

***Abstract* - Public passenger transport is the primary mode of urban mobility. However, it is highly dependent on fossil fuels, which represents a significant threat to the environment due to increased carbon emissions and air pollutants. This dependence contributes to the warming of the regions where these transportation systems operate. To address this challenge, energy efficiency measures must be implemented within urban transport infrastructures to ensure sustainable energy use. To mitigate pollutants and save energy derived from fossil fuels, wind turbines can be integrated into Bus Rapid Transit (BRT) System stations. This initiative requires a thorough characterization of the BRT system, including the identification of key variables to facilitate the implementation of such a solution.**

Keywords: Wind energy, wind turbines, public passenger transport.

I. INTRODUCTION

Approximately 80% of the world's energy is derived from non-renewable fossil fuels, including coal, oil, and natural gas [1]. In urban areas, public transportation is a significant contributor to air pollution, responsible for more than one-third of CO_2 emissions from end-use sectors. Recent data from 2022 indicate a concerning trend: global CO_2 emissions from the transport sector increased by over 250 Mt CO_2 to nearly 8 Gt CO_2, representing a 3% increase compared to 2021 [2].

Technological advances play a pivotal role in addressing environmental concerns in transportation, particularly in the development of energy and pollutant reduction systems for private vehicles. Nevertheless, public passenger transport has not received the same level of attention. Consequently, two significant challenges emerge: the promotion and evaluation of the adoption of renewable energy sources and the improvement of transportation efficiency in order to achieve sustainability goals.

One potential solution is to utilize wind energy, which has emerged as a significant contributor to global power generation. The utilization of wind energy not only reduces CO_2 emissions but also contributes to the mitigation of climate change by promoting the use of clean, renewable energy sources. The conversion of wind energy into electrical power enables its effective utilization in the operation of transportation infrastructure, thereby providing a sustainable and environmentally friendly alternative.

This article thus examines the potential of integrating wind turbines into BRT system stations as an alternative solution to achieve energy savings. The article is structured as follows: Section 2 provides a literature review on wind energy, wind turbines, and transport energy consumption; Section 3 provides a characterization of the transport system, detailing the utilization of wind turbines and the essential implementation variables; Section 4 presents a theoretical proposal for the integration of wind turbines in a key corridor of Mexico City for the BRT System; and finally, conclusions drawn from the implementation of wind turbines are presented.

I. LITERATURE REVIEW

A. *Energy consumption in the transport sector*

Global energy consumption reached 422,117.52 petajoules (PJ) in 2021, representing a significant increase of 5.04% over the previous year. While efforts were made to reduce the carbon footprint, there were mixed trends in the consumption of energy sources. Consumption of coal and coal derivatives decreased by 0.54%. However, crude oil consumption increased by 14.18% over 2020, followed by natural gas with an increase of 6.09%. Petroleum products and electric power experienced significant increases, rising by 5.85% and 5.79%, respectively. In contrast, renewable energies experienced the smallest increase, rising by 4.20% over the previous year. [3] (Figure 1).

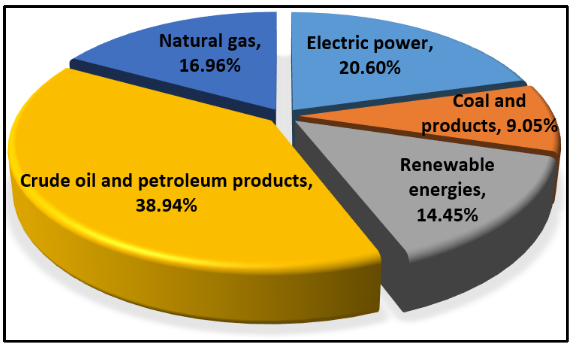

Figure 1. Global energy consumption by energy, 2021 [3].

In terms of energy consumption, the transportation sector accounted for a significant share, amounting to 26.68% (112,628.35 petajoules or PJ), which was largely driven by the combustion of fossil fuels. This increase can be attributed to the post-confinement recovery following the SARS-CoV-2 virus outbreak, which resulted in a 7.71% increase compared to the previous year, 2020 (see Figure 2). In the transportation sector, the transportation engine accounts for the largest share of energy consumption, representing 90.63% of the total [3] (see Figure 3).

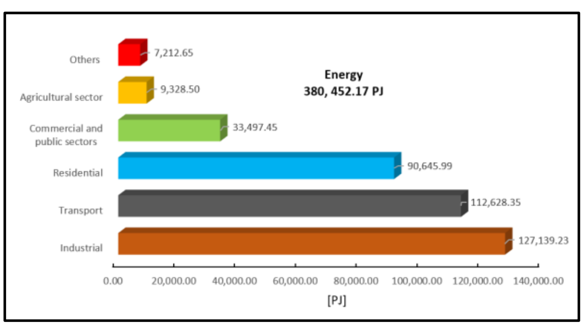

Figure 2. World energy consumption by category, 2021 [3].

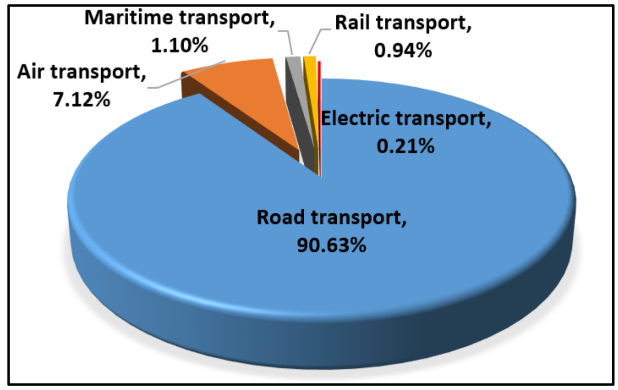

Figure 3: Energy consumption in the transportation sector [3].

The analysis of energy consumption is closely related to greenhouse gas (GHG) emissions, with transportation being a significant contributor to both. As indicated by [4], transportation is accountable for 38% of global energy consumption and 37% of GHG emissions. Mexico is ranked eighteenth in the international ranking of nations with the highest energy consumption [3], with its transportation sector consuming 46% of the energy produced and contributing 42% of GHG emissions, exceeding the world average [5]. In 2021, fuel consumption in Mexico's transportation sector reached 2,784,644 petajoules (PJ), representing a 63.45% increase over 2020 and accounting for 51.98% of the country's total energy consumption. A mere 0.2% of the total energy consumed in the transport sector is attributed to electricity supplied to electric transport, amounting to 5,693 PJ [6]. This underscores a significant obstacle in the transition to a more sustainable and energy-efficient transportation system in Mexico. Consequently, it is of the utmost importance to implement strategies that will result in a reduction in energy consumption if the United Nations' Sustainable Development Goals are to be achieved. The utilization of alternative energies, such as wind energy, appears to be a promising avenue for reducing energy consumption and associated emissions.

B. *Wind energy.*

Wind energy is a renewable energy source that harnesses the kinetic power of the wind using wind turbines. The energy is then transformed into electrical energy, which results in a significant reduction of polluting emissions by operating without generating greenhouse gases. Wind turbines are strategically installed onshore and offshore, featuring ingenious structures composed of large rotors equipped with blades. The wind exerts a force on the blades, causing them to rotate and thereby activating an internal electric generator. The efficiency of a wind turbine in converting energy is contingent upon several factors, including wind speed and the turbine's characteristics, such as generator capacity, hub height, and rotor diameter. These elements collectively determine the turbine's ability to capture and convert wind energy into electricity. Wind power technology is becoming a cornerstone in the transition to a sustainable energy future. It provides a clean, renewable alternative that diversifies energy sources and helps combat climate change [7].

Currently, energy recovery systems are employed to capture and transform the energy generated during braking or deceleration into a form that can be utilized as electrical energy. The integration of these systems into buses and trains allows for the reinvestment of otherwise wasted energy, thereby enhancing the overall energy efficiency of the system. Empirical evidence indicates that these systems can reduce energy consumption by up to 20%, thereby becoming a pivotal element in the optimization of the sustainability of transportation networks [8].

In the global effort to identify sustainable energy alternatives to fossil fuels, wind power has emerged as a significant contributor to electricity production. The widespread adoption of wind power contributes to the diversification of the energy mix and plays a pivotal role in the global effort to combat climate change. Wind power offers a renewable energy source that mitigates greenhouse gas emissions and facilitates the transition to a resilient, low-carbon energy economy. There has been a notable global expansion in the installed capacity of wind power, with substantial investments being made in both onshore and offshore wind farms. China, the United States, Germany, and Spain are leading nations that have made significant commitments to the energy transition, with notable installed wind power capacity [9].

These collective endeavors serve to illustrate the potential of wind energy to mitigate climate change. It is estimated that a rapid expansion of installed wind power capacity could significantly delay the 2°C warming threshold relative to pre-industrial levels [10].

In 2017, Mexico had an installed electricity production capacity of 75.69 gigawatts (GW), of which around 29.5% came from clean energy plants, including wind power. It is worth noting that the Isthmus of Tehuantepec region in Oaxaca is home to one of the highest densities of onshore wind turbines in the world. La Guna Sicarú wind farm in this region comprises 96 turbines generating 252 megawatts (MW), making it an important site for wind energy development in Mexico [11][12].

These developments underscore the abundance of sites in Mexico with substantial complementarity with energy sources. Although some locations are already in use, there are still untapped areas in the central to northern regions of the country that offer opportunities for the development of renewable energy generation systems. This underscores Mexico's substantial potential for integrating solar and wind energy into its energy matrix [13].

C. Wind turbines

In order to reduce the emission of polluting gases resulting from the combustion of fossil fuels, it is necessary to transition towards an industrial model and a lifestyle that prioritizes the use of sustainable and environmentally friendly energy alternatives. This necessitates the adoption of cleaner primary energy sources and their conversion to usable energy in an efficient manner, while simultaneously safeguarding the health of the planet and promoting a responsible energy future.

In this endeavor, extensive research has been conducted on the utilization of wind turbines. A wind turbine, also known as a wind generator, is a device designed to convert the kinetic energy of the wind, a natural and renewable source, into electricity. In contrast to a fan, which consumes electricity to generate wind, a wind turbine functions in reverse by harnessing the energy of the wind to generate electricity [14].

Wind turbines can be classified according to two key criteria: their power generation capacity and the position of their shafts. In terms of their capacity to generate power, wind turbines are classified into three categories: low-power, medium-power, and high-power turbines.

The shaft position allows for the classification of wind turbines into two categories: vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT). The Savonius type of VAWT comprises two half-cylinders of equal diameter positioned parallel to the vertical axis of rotation. The Darrieus type of VAWT features two or three oval-shaped blades with an aerodynamic profile and offers minimum starting torque. Both types of wind turbine rely on differential wind forces to induce rotation. HAWT includes slow wind turbines that are equipped with a large number of multiple blades, which cover a significant portion of the rotor surface. Due to their relatively slow rotational speed, wind turbines of this type are more suitable for tasks such as water pumping than for electricity generation. In contrast, fast wind turbines are designed for the specific purpose of electricity generation, while intermediate-speed wind turbines, which typically have three blades, are used for electricity production by coupling with an alternator.

Vertical axis wind turbines (VAWT) exhibit several advantages over horizontal axis turbines. The vertical symmetry of these turbines obviates the necessity for orientation systems to align the turbine axis with the wind direction. Furthermore, VAWTs necessitate less complex maintenance procedures due to their reduced ground clearance. Furthermore, if they operate at a constant speed, there is no need to incorporate pitch change mechanisms, which translates into lower installation costs.

However, it should be noted that each wind turbine is adapted to specific environments and needs (Table 1). In urban settings, mini-wind turbines are the most prevalent and adaptable wind turbines due to their compact size and inherent safety features. Figure 4

TABLE 1. CLASSIFICATION OF WIND TURBINES

	Types of Wind Turbines			
	Horizontal Axis	***Vertical Axis***	***Offshore***	***Mini wind turbine generators***
Advantages	High efficiency	Less space	Increased energy production	Easy Installation
Disadvantages	Requires a lot of space	Less efficiency	High cost	Limited production
Ideal Use	Large wind farms	Urban areas	Offshore	Individual use or small quantities
Estimated power in (kw)	2000 8000 kW	10 – 100 kW	Up to 10000 Kw or more	5 50 kW

Source: Own elaboration

Figure 4: Mini wind turbine generation

Source:(Ovacen, 2024) [15]

D. BRT Systems

The Bus Rapid Transit (BRT) system represents a public transportation solution designed to enhance urban mobility. It encompasses several features, including dedicated bus lanes, high-quality stations, and efficient fare collection systems. These components function in concert to provide dependable and expedient transportation services, while requiring less investment and implementation time than rail or subway systems. The BRT system is renowned for its capacity to enhance urban mobility by reducing congestion and travel times. In the case of Mexico, BRT systems such as the Metrobus in Mexico City have implemented analogous strategies to enhance public transportation and concurrently diminish vehicular congestion and pollution [16].

The paper entitled 'A study on Bus Rapid Transit (BRT) system' focuses on economic and air pollution analysis in Tehran [17]. It investigates the efficiency of Tehran's BRT system by simulating ten different scenarios using Aimsun software. The scenarios aim to improve the efficiency of the system by implementing bus-only lanes, reducing bus intervals, activating traffic signals, and revising bus stations. The study demonstrates that converting shared lanes to dedicated lanes can generate significant benefits. These benefits include a 2.95% reduction in travel time, a 9% decrease in CO emissions, a 1.13% decrease in PM emissions, a 3.45% decrease in NOx emissions, and a 5.3% reduction in fuel consumption per kilometer. In addition, replacing fixed signs with activated signs along the route resulted in even greater improvements. Travel times were reduced by 6.31%, CO emissions by 25.9%, PM emissions by 3.42%, NOx emissions by 6.2% and fuel consumption by 5.26%.

This analysis offers insights into the potential of bus rapid transit (BRT) systems to optimize public transportation, enhance efficiency, reduce pollution, and contribute to sustainable urban development. These findings are pertinent to the Mexican context and present potential strategies for enhancing transportation systems while mitigating environmental impacts.

The study, entitled "Performance Evaluation in BRT Systems: An Analysis to Predict BRT System Planning," provides a comprehensive examination of the BRT system. Stochastic Petri Nets (SPN) are employed to assess the performance of the system, with a particular focus on key metrics such as the average system size, average queue size, average queue waiting time, and the probability of a user missing the bus. The model evaluates a variety of scenarios to optimize BRT planning and operation. This is achieved by incorporating variables such as bus intervals and the number of vehicles on the route.

The scenario identified indicates that the use of 300-second head intervals with five vehicles on the route results in a reduction in passenger waiting times. This approach offers a valuable tool for public transport system managers to evaluate and improve BRT performance. By considering a range of configurations and operational conditions, it is possible to achieve significant improvements in terms of efficiency, customer satisfaction, and sustainability. This analytical framework provides decision makers with the information necessary to optimize BRT systems, resulting in more efficient operations, enhanced service quality, and greater sustainability in urban transport networks.

II. BRT SYSTEM AND VARIABLE WIND TURBINES CHARACTERIZATION

For the generation of the proposal of the present project, a quantitative methodology of 4 stages is followed:

1. Characterization of the system, where variables of the urban wind turbine and transport variables are determined.
2. Characterization of the energy consumption in the system: to recognize the energy consumption in the station.
3. Determine the type of wind turbines: the specific characteristics of the wind turbines are considered, as well as the feasibility of their implementation in urban areas.
4. Planning of the special distribution of the wind turbines.

For which several variables must be considered for the implementation of wind turbines. These include:

A. Variables Influencing Energy Production

In the context of wind turbine-based energy production, the primary variables that impact the process are wind speed, air density, and blade radius. It is of the utmost importance to gather pertinent data on these variables [18].

B. Wind turbine characteristic variables.

For wind turbines, the essential variables required are the following [19]:

- Power: represents the main characteristic parameter of a wind turbine and denotes the amount of energy it can generate per unit time. Small-scale turbines for domestic use usually start with 1 kilowatt, while offshore turbines can reach up to 10 megawatts.
- Wind response curve: This curve illustrates the relationship between the power output and wind speed of a wind turbine. It generally consists of three regions: the region where wind speed is insufficient for production, the range of speeds from synchronization with the grid to maximum power production, and the range of speeds within which the turbine can operate effectively in both gusty and sustained winds, as well as the range where the turbine must be shut down.
- Wind turbine/generator type: Wind turbines use generators to convert the mechanical energy of the rotor into electrical energy. Generators can be either synchronous or asynchronous, and this distinction significantly affects the overall turbine design.
- Gearbox type: The gearbox inside a wind turbine plays a crucial role in transmitting power from the rotor to the generator. There are several types of gearboxes, including single and multi-stage parallel shaft gearboxes, single and multi-stage planetary shaft gearboxes, and mixed gearboxes, which are commonly used in high-power wind turbines.
- Number of blades: Wind turbines can have one, two or three blades, although smaller models occasionally have more than three (always an odd number).
- Nacelle height: Refers to the height of the nacelle measured from its base to the center of the nacelle or the height of the rotor shaft. Nacelle heights vary significantly and depend on the turbine power, which determines the length of the blades.
- Blade length: The blades are crucial for converting the kinetic energy of the wind into rotating mechanical energy. The length of the blades is determined by the turbine power.
- Maximum height: This is the sum of the nacelle height and the blade length.
- Efficiency: The efficiency of the wind turbine depends on the speed curve and varies accordingly.
- Swept area: This denotes the area covered by the rotating blades, resembling the area of a circle.
- Rotational speed (range): In most cases, this is presented as a range. For high-power, grid-connected turbines, the rotational speed is typically around 15 revolutions per minute (rpm) and fluctuates between 10 and 15% depending on wind speed. Larger turbines tend to have lower rotational speeds.
- Blade orientation system: This can include turbines with no orientation system, those with hydraulic orientation systems, and those with electric orientation systems.
- Generation voltage: Wind turbines generally generate electricity at low voltages, with the common voltages at the generator terminals being 400 volts and 690 volts, both in three-phase current.
- Wind turbine output voltage: While domestic or low-power generators can generate directly at low voltage, medium or

high-power generators usually require a transformer to raise the voltage to the substation connection voltage.

- Type of transformer: Possible transformers to step-up the generation voltage to transport voltage include integral fill transformers and dry transformers, the latter being the most common.
- Transformer location: The step-up transformer can be located at the rear of the nacelle, on top of the wind turbine or at the foot of the tower.
- Nacelle dimensions: Parameters such as height, length and width of the nacelle are crucial for transport to the site and erection.
- Nacelle weight: understanding the weight of the nacelle, along with its dimensions, is critical in determining the proper transportation method for its movement and installation on top of the tower.

C. Transport system variables.

The Bus Rapid Transit (BRT) system comprises a dedicated bus lane, along with bus-level boarding platforms and the collection of fares at stations, which collectively facilitate the boarding process. To implement wind turbines, it is necessary to determine the number of stations along the route, the distance between each station, the number of traffic lights along the route, and the average speed of the buses.
Figure 5 and Table 2, illustrates the system configuration, where node A represents the number of stations along the route and node B represents the number of traffic lights along the route.

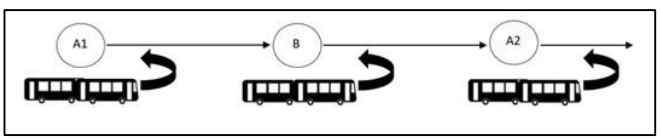

Figure 5: BRT system in nodes. Source: Own elaboration

TABLE 2. TABLE OF NODES IN THE BRT SYSTEM

Node type	**Definition**
Type A	= Number of stations on the route
Type B	= Number of traffic lights on the route

Source: Own elaboration

Once this information has been obtained, step 4 of the methodology proposed for this study can be carried out, which is detailed below.

III. TRANSFORMING THE BRT SYSTEM FOR A GREENER FUTURE (PROPOSAL FOR THE IMPLEMENTATION OF WIND TURBINES FOR THE BRT SYSTEM)

It is therefore proposed that wind turbines be integrated into the BRT system. The proposed solution entails the installation of vertical wind turbines at each station and traffic light, with the objective of maximizing the efficiency of power generation. Each turbine is connected to a substation, which boosts the voltage to power the station lighting system (Figure 6 and Table 3).

Furthermore, the proposal includes the deployment of batteries to store surplus energy. The stored energy can then be transported to charging centers to power the lines equipped with all-electric buses.

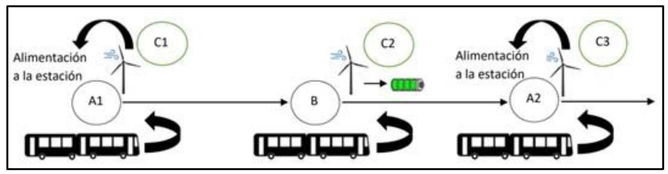

Figure 6: BRT system proposal Source: Own elaboration

TABLE 3. PROPOSED NODE TABLE IN THE BRT SYSTEM

Node type	**Definition**
Type A	Number of stations on the route
Type B	Number of traffic lights on the route
Type C	Number of wind turbines on the route

Source: Own elaboration

In consideration of the physical attributes of the BRT system infrastructure, the Savonius turbine is a suitable option for urban applications due to its simple microturbine design and its ability to operate at relatively low wind start-up speeds.

For the current analysis and implementation of wind turbines to be carried out correctly, it is necessary to link them to those agencies with decision-making power within the country's electricity sector. This implies that:

1. Implementing the requisite legal and regulatory changes to facilitate the development of wind energy in the country.

2. To conduct the requisite studies to ascertain the impact of the implementation of urban wind turbines in the BRT system.

3. It is recommended that the preparation and specialization of technical personnel in wind energy development and implementation be promoted.

The proposal is currently in its initial planning phase, during which the conceptual model and the necessary data collection variables are being outlined. Subsequent phases will entail the calculation of turbine placement distances, the determination of battery specifications for energy storage, the design of the necessary voltage lines, and the estimation of the energy yield of the wind turbine system. The objective is to quantify the potential energy savings that would result from the implementation of the system.

IV. CONCLUSIONS

Public transportation represents a vital component of urban infrastructure, providing daily mobility for millions of individuals. However, the sector is heavily reliant on non-renewable fossil fuels, such as coal, oil, and natural gas, which present significant sustainability challenges. To address this problem, innovation and the adoption of clean technologies are essential for the transition of public transport towards greater sustainability.

Wind turbines appear to offer a promising solution in this context, particularly in the context of bus rapid transit (BRT) systems. The integration of wind turbines in BRT systems not only reduces dependence on fossil fuels but also promotes an efficient, reliable, and environmentally friendly transportation model aligned with long-term sustainable development goals.

This represents a significant step towards energy autonomy and cost reduction, while simultaneously demonstrating a commitment to innovation and environmental stewardship. BRT systems play a pivotal role in alleviating traffic congestion and enhancing air quality in urban areas. The investment in the retrofitting of public transport infrastructure with solar panels and wind turbines has the potential to generate clean, renewable energy, to reduce dependence on fossil fuels, and to promote sustainability goals.

The definition of variables for the implementation of wind turbines in Bus Rapid Transit (BRT) systems serves as the foundation for the development of simulation models. These models are of critical importance in guiding decisions regarding the adoption of clean energy to enhance the autonomy of transportation systems and to mitigate dependence on fossil fuels. This approach represents a significant advance towards achieving the sustainability goals set by the United Nations.

These preliminary steps serve to establish the foundation for the development of a comprehensive simulation. The simulation will be employed to assess the current energy consumption of the BRT system in comparison to the anticipated consumption following the integration of the wind turbine system.

Consequently, future work will entail the simulation of the system and its energy consumption, as well as the reduction of consumption once the proposal is implemented.

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