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Benchmarking and Strategic Analysis of Metro System; Enhancing Sustainability and Efficiency

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Abstract

With the growth of urbanization and demands towards sustainability in transportation, metropolitan systems are becoming vital elements of infrastructure in modern cities. The current study is aimed at conducting a benchmarking analysis of 47 metropolitan systems worldwide regarding the two sustainability dimensions, energy efficiency, and indoor air quality (IAQ). The research utilizes such statistical methods as correlation analysis, multiple regressions, and Monte Carlo simulations to analyze the impact of various operating parameters like the number of lines, stations, vehicles, length of the network and number of passengers on energy consumption and PM2.5 concentration. To enhance comparison of metropolitan systems, energy consumption indicators were assessed based on normalization. Based on the findings, there is a high positive correlation between the intensity of operations and total energy usage, with vehicle fleet (r = 0.9738) and vehicle kilometers (r = 0.9404) being the most influential variables. Metro systems with a larger capacity, for instance, Tokyo (95,798 GWh per year), have a higher demand for total energy because of the extent of the operation and high passenger numbers. This does not imply inefficiency but the sheer size of the metro system. Smaller metro systems use fewer amounts of energy, whereas some systems, like Singapore, provide relatively good air quality ($PM_{2.5}$ = 24.5 µg/m³). A significant difference in the $PM_{2.5}$ index was noted among different metro systems, with higher values in cities like Barcelona (102 µg/m³) and Beijing (163 µg/m³). Observations from real-world examples of metro systems like Santiago, Amsterdam, and Paris have pointed out the success of various strategies, which include incorporating renewable energy sources, regenerative brakes, and effective ventilation. According to simulations, policy instruments can help stabilize energy consumption and bring down air pollution levels, as seen in the metro system of Sydney. The analysis concludes that there are certain factors that determine whether a metro system is sustainable. These include the size of the system, intensity of operations, and environmental conditions, among others.
Keywords: **Metro systems; Energy efficiency; Sustainable transportation; Indoor air quality; PM2.5.**

1. Introduction

Urban transport plans constitute the very core of sustainable development, and metro rail transport plans are the best illustrations of mass transit modes. Metro rail transport schemes enable mobility in a high-capacity mode but at reduced traffic congestion, greenhouse gases, and urban sprawls compared to non-public motors. These advantages are challenged by, however, by two primary flaws: excessive energy consumption, as well as degradation of indoor air quality (IAQ), particularly within underground transportation. This research provides a comprehensive benchmarking analysis of 47 world metro systems to determine drivers of energy use and particulate matter (PM2.5) emissions, to inform planning towards sustainable urban transport. Energy Consumption and Air Pollution Metro systems are major city consumers of electricity, and energy loads created through traction in trains, operations in stations, and ventilation. While metros consume 15–25% less energy per passenger-kilometer than buses or private vehicles (Railway Transport Efficiency, 2023), network size maintains overall energy consumption high. For instance, the Tokyo Metro, being one of the busiest metros, uses up to 95,798 GWh of power per year. Also, the London Underground is responsible for a significant portion of the city's consumption of electricity, which is over 10% (Transport for London, 2011). Apart from that, the air quality in such systems, particularly those parts that operate underground, may be characterized by high $PM_{2.5}$ readings compared to acceptable ones, as proposed by WHO, i.e., 25 µg/m³ for a 24-hour period. According to data from various cities, the average value of $PM_{2.5}$ exceeds the recommended norm: Barcelona – 102 µg/m³, Beijing – 204 µg/m³, and Chicago – 284 µg/m³ (Moreno et al., 2020; Baraniuk, 2023).

These pollutants are produced through mechanical processes (brake wear, wheel-to-rail abrasion), as well as outdoor air intake (Querol et al., 2012). To ensure comparability between cities of different sizes, this study considers normalized performance indicators rather than relying only on total values.

2. Problem statement.

Despite their benefits, metropolitan transit systems are experiencing some difficulties when it comes to IAQ and energy consumption. Poor indoor air quality in these structures has been shown to lead to high levels of particulate matter (PM) emissions, especially $PM_{2.5}$, that can travel deep inside the lungs and reach the blood stream. The sources of particulate matter in metro stations are mainly internal mechanisms, such as wearing down brakes and friction between wheels and the railway track, and outside air leaking into the station. Because of their size, $PM_{2.5}$ can stay airborne longer than other particles and thus pose a risk to health through inhaling them. There have been

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multiple studies demonstrating how exposure to particles leads to developing different respiratory and cardiovascular diseases.

In addition to the mentioned issue, another one faced by metro stations is their high consumption of energy within cities. They require energy to operate trains, light stations, provide them with proper ventilation and climate control. The larger the network becomes, the greater its energy consumption gets. Thus, an important question that needs to be answered is the extent to which operational parameters affect energy consumption and air pollution. Such information will help in formulating appropriate measures for improving energy efficiency and reducing pollutants in the atmosphere. In this study, $PM_{2.5}$ refers to ambient air conditions within metro environments inside station and tracks rather than outdoor city-level pollution.

3. Literature Review

3.1 Metro Air Quality

Particulate matter (PM), particularly PM2.5, is a critical health concern in metro systems due to its high concentration in enclosed spaces and ability to penetrate deep into the lungs. Studies from cities like Montreal, New York, London, Paris, Seoul, and Chengdu have shown that PM levels vary based on system design, tunnel length, braking mechanisms, ventilation efficiency, and cleaning practices (Salma et al., 2007; Moreno et al., 2014; Woo et al., 2018). PM2.5 levels often rise during transitions from overground to underground tracks, with recorded concentrations ranging from 11–74 µg/m³ and PM10 from 13–89 µg/m³. In cities such as Barcelona, Athens, and Porto, PM2.5 levels were significantly higher than outdoor air, with iron particles being a dominant component (Querol et al., 2012; Moreno et al., 2015). This shows that the amount of $PM_{2.5}$ in metros is significantly impacted by factors such as the metro's architecture, ventilation system performance, and operation conditions.

3.2 Energy Consumption in Metro Systems

Underground stations are major energy consumers due to continuous lighting, ventilation, and HVAC needs, with annual energy use reaching up to 152 kWh/m² compared to 91 kWh/m² for overground stations. Station size and passenger volume are closely linked to electricity consumption (Sustainable Research, 2018). For instance, London Underground is among the UK's largest energy consumers, and China's urban rail systems consumed 11.1 billion kWh in 2016 alone (Transport for London, 2011; National Energy Administration, 2017), underlining the need for improved efficiency. This means that both infrastructural features and passenger numbers contribute to the total amount of energy consumed in metros.

3.3 Renewable Energy Projects

To address energy and sustainability concerns, several metro systems are investing in renewable energy. Santiago's metro plans to generate 60% of its electricity from solar and wind through long-term power purchase agreements. The Netherlands' entire rail network is powered by wind, and San Francisco's BART aims for 100% zero-carbon electricity by 2045, with solar installations underway. Innovations such as Green rail's solar railway sleepers (Italy), solar traction wires (UK), and solar farms in India and Melbourne further illustrate the global shift toward clean energy in urban rail systems. All this shows an increasing trend towards the use of renewable energy in metro transportation.

4. Research Gaps and Objectives

Previous literature has addressed metro consumption of energy (Guan et al., 2018) and PM2.5 pollution (Moreno et al., 2014) primarily as standalone events. It is uncommon to find any literature that has made a comprehensive examination of how operation parameters i.e., fleet size, route length, and passenger load are simultaneously influencing energy efficiency and the air environment. This shortcoming foregoes providing transit authorities with a vision pathway to sustainability action.

This study remedies the above-mentioned gaps and sets out to achieve the following essential objectives:

- Analyzing the Connection between Operational Quantities and Sustainability Indicators: Analyze the relationship between operational quantities like fleet size, network length, ridership, and passenger kilometers in relation to energy consumption and levels of PM2.5.
- Establish Primary Drivers of Energy Consumption and Air Quality: Pinpoint the major operational drivers responsible for affecting the levels of both energy consumption as well as particulate matter levels in metro operations.
- Recommend Solutions for Maximizing Efficiency and Sustainability: Develop actionable recommendations from the correlation analysis for maximizing energy efficiency and reducing air pollution in metro systems.
- Predict Future Patterns for Sustainable Metro Systems: Use findings to forecast future patterns in energy usage and air quality, providing a template for long-term sustainability and operational efficiency.

Through the achievement of these targets, this study aims to provide valuable contributions to metro operators and policymakers on how to improve the sustainability of metro systems, thus facilitating the achievement of the United Nations Sustainable Development Goals (SDGs) objectives, SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities).

5.Methodology

5.1 Data Collection

5.1.1 Selection of Metro Systems

A total number of 47 metro rail systems were chosen to make sure that the chosen sample included a variety of metro rail systems from all over the world, covering different geographic locations, size and other factors.

To choose the samples, we considered the availability of reliable data about operational parameters and indicators of sustainability.

The metro rail systems analyzed in the paper include metro rail systems of Europe, America, Asia and Australia including such cities as London, Paris, New York, Tokyo, Beijing and Sydney. Appendix A provides an exhaustive list of the Metro system with cities. All the data used for the research can be obtained upon request.

5.1.2 Data Sources:

- Metro authority reports (operational/sustainability data)
- Government and city transport databases
- Peer-reviewed journals
- Industry reports and consultancy publications

5.1.3Variables and Indicators:

Operational Metrics	Sustainability Indicators
Number of lines and stations	Total energy consumption (GWh)
Network length (km)	Peak PM2.5 levels (μg/m³)
Number of vehicles/cars	
Annual ridership	
Vehicle-km and passenger-km	

5.2 Data Validation

To achieve the consistency and accuracy of the data, the data set was validated and preprocessed. Cross-validation was done on the data obtained from various sources, giving priority to the most recent and reliable sources when there was any inconsistency.

The data set was cleaned by finding out the missing data and the outlier data. Missing data was treated accordingly by applying imputation methods or omitting the missing data.

Standardization was carried out on all the data sets, converting all the variables to uniform units, for instance, energy in GWh and $PM_{2.5}$ in $\mu g/m^3$.

5.3 Correlation Analysis

Correlation analysis was performed to determine the extent and nature of the relationship between the variables involved and the sustainability parameters.

Pearson's Correlation Coefficient (r) was applied to calculate the linear relationship between the variables and is computed using the following formula:

Formula:

$$r = n(\sum xy)-(\sum x)(\sum y) / \sqrt{(n\sum x^2-(\sum x)^2)(n\sum y^2-(\sum y)^2)} \quad (1)$$

Such an analysis will enable us to determine the important variables that influence energy usage and $PM_{2.5}$ emissions.

5.4 Regression Analysis

Regression models were formulated for a deeper analysis of the impact of operational parameters on sustainability parameters.

The energy consumed and $PM_{2.5}$ emissions were considered as the dependent variables, whereas the operational parameters were used as independent variables. The regression equation generally takes the following form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \epsilon \quad (2)$$

Validation Techniques:

- Split-sample training/testing
- K-fold cross-validation
- Residual analysis to confirm model robustness

Result Interpretation

Metric	Meaning
β Coefficients	Change in dependent variable per unit of independent variable

R^2 Value	Variance explained by the model
Significance (p)	Indicates statistical reliability of predictors

5.5 Benchmarking

Comparisons were made among different metros based on their performances in relation to their energy use and air quality. Normalized metrics such as per passenger or per distance were considered in the comparison process to make comparisons between metros that differ in size.

This was achieved by means of benchmarking, which facilitated the identification of best-performing metros and good practice among them.

5.6 Scenario Forecasting

To determine future trends that could develop, a scenario analysis was carried out using simulation methods. The most important input factors involve the rate at which energy demand grows, any change in the number of riders, and any reductions in the number of emissions. These factors varied within a certain range in order to take into consideration uncertainty and generate various outputs.

Various parameters that were considered included the implementation of renewable energy, improved energy efficiency, and emission reduction policies.

The following are some scenarios that were considered during the analysis:

- Use of more renewable energy sources
- Efficient energy use
- Policies on air quality and emissions

Results that are probabilistic in nature were generated.

5.8 Strategy Development

In consideration of the outcomes of the analysis carried out, some strategic approaches have been formulated for enhancing the sustainability of the metro system.

The proposed strategies include:

- Efficiency in operation
- Technological advancements
- Strategic policy formulation

The suggestions have been developed based on the findings of the correlation and regression analyses.

6. Data Presentation and Analysis

6.1 Overview of Dataset

The analysis involves 47 metropolitan railway systems globally based on selected indicators for their operations and sustainability performance. The operation variables include network size (numbers of lines, stations, and kilometers of lines), train fleet (number of trains and cars), and ridership variables (riders, train-kilometers, and passenger-kilometers). Sustainability performance is measured in terms of the total annual energy consumption (in GWh) and the level of PM2.5 (in µg/m³).

Where data on energy consumption were not directly available, an estimate of the figure was made by considering the mode share ratio (10–33%).

6.2 Correlation Analysis

Table 1: Pearson Correlation Coefficients (n = 47 metro systems)

Independent Variable	PM2.5 (µg/m³)	Energy Consumption (GWh)	Statistical Significance
Number of lines	0.496	0.791	$p < 0.01$
Number of stations	0.450	0.788	$p < 0.01$
System length (km)	0.491	0.772	$p < 0.01$
Number of cars	0.347	0.974	$p < 0.001$
Number of vehicles	-0.259	-0.288	$p > 0.05$ (NS)
Passenger-km ($\times 10^6$)	0.056	0.872	$p < 0.001$
Vehicle-km ($\times 10^6$)	0.490	0.940	$p < 0.001$
Annual ridership ($\times 10^6$)	0.062	0.759	$p < 0.01$

NS = Not Significant ($p > 0.05$)

Key findings:

Energy usage is positively correlated with:

- Number of vehicles ($r = 0.974, p < 0.001$)
- Vehicle-kilometer travel ($r = 0.940, p < 0.001$)

- Passenger-kilometer travel ($r = 0.872$, $p < 0.001$)

Therefore, energy usage is closely associated with the scale and intensity of system operations. There are some moderate correlations found between infrastructure factors and energy use ($r \approx 0.77$-0.79). $PM_{2.5}$ values have only a moderate correlation with system size ($r \approx 0.45$-0.50) and have no statistically significant association with passenger counts and passenger-kilometers. Small inverse relationship between vehicle number and $PM_{2.5}$ ($r = -0.259$) could imply that advanced technology is a factor behind improved air quality.

It is thus clear that energy usage is affected by internal operational factors, while $PM_{2.5}$ depends on external factors as well.

6.3 Regression Analysis

Table 2: Regression Model Summary

Indicators	P.M.2.5		Total energy	
	Regression equation	R^2	Regression equation	R^2
No. of lines	y = 0.0488x + 3.5464	0.2464	y = 0.0001x + 4.696	0.6266
No of stops	y = 1.0149x + 52.888	0.2031	y = 0.0025x + 76.779	0.6216
Length	y = 1.7492x + 32.275	0.2420	y = 0.003x + 82.059	0.5958
no. of cars	y = 4.8387x + 606.55	0.1206	y = 428.87+2E-05x	0.9492
No. of vehicles	y = -0.5696x + 268.36	0.0671	y = -5E-09x2 - 0.0014x + 183.12	0.0832
Pass. Km	y = 6E+06x + 7E+09	0.0031	y = 704977x + 7E+08	0.7597
Vehicle km	y = 2E+06x - 4E+07	0.2400	y = 28441x + 4E+07	0.8845
Annual ridership	y = 769463x + 7E+08	0.0038	y = 21908x + 5E+08	0.5761

Regression models were developed to examine the impact of operational variables on energy consumption and $PM_{2.5}$ concentrations further. Regression coefficients are influenced by variable scaling (e.g., passenger-km expressed in large units) and should be interpreted in relative rather than absolute terms.

Important findings:

- Energy consumption:
  - The model has good predictive power with respect to variables concerning vehicles (number of cars, number of vehicle-kilometers), $R^2 > 0.85$.
  - Model has moderate predictive power with respect to infrastructure related variables (number of lines, number of stations, network length), $R^2 \approx 0.60$.
- $PM_{2.5}$ concentration:
  - All regression models have poor predictive power, $R^2 < 0.25$; therefore, we may assume that there are more important factors explaining the fluctuations in air quality.
- Moderate correlations were found between ridership and passenger-kilometers on one hand, and energy consumption on another, $R^2 \approx 0.57$-0.76.

6.4 Discussion

Energy Consumption

As seen from the results, the greater the size of the system and activity level, the more energy is consumed. Vehicle count and vehicle kilometers are variables that exert the greatest effect on energy consumption.

These results are consistent with what was expected since large-scale metros need additional energy expenditure due to the greater energy traction, station operations, and facilities needed to support the activity.

$PM_{2.5}$ Concentration

On the other hand, $PM_{2.5}$ concentration appears to have very little correlation with all the studied variables except for a weak negative correlation with the vehicle count.

This implies that the pollution level inside metros depends not only on various internal processes but also on outside conditions including the degree of pollution of the city and environment policies.

Comparison Between Systems

Overall, the results imply that comparisons between systems of different sizes would require considering normalized metrics rather than simple energy consumption numbers since larger cities naturally consume more energy.

6.5 Limitations:

Limitations to consider:

- The energy consumption of certain modes was assumed based on modal split ratios, which might lead to inconsistencies.
- Certain external variables like climate variables, tunnel configuration, and ventilation systems were not incorporated into the models.

- The $PM_{2.5}$ readings could differ depending on the sampling techniques and sampling sites inside the metro networks.

6.6 Conclusion:

The results reveal that energy utilization in metros is highly dependent on internal operating characteristics such as the number of trains in operation and train service frequency. Conversely, $PM_{2.5}$ concentrations do not have a direct correlation with the above parameters and depend on other more general environmental and system characteristics. From the results above, it can be deduced that for the successful adoption of a sustainable strategy in metros, one must consider both internal operations and the external environment.

6.7 Graphical Representation

Scatter plots were generated in Excel to visualize relationships between key indicators and the two primary metrics: PM2.5 concentrations and total energy consumption. Each plot includes a fitted trendline, corresponding regression equation, and R^2 value to illustrate the strength and direction of the relationship. These visuals offer a clear depiction of data trends and variability for some indicators, supporting the statistical analysis.

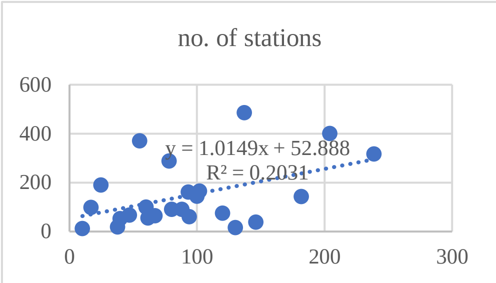
<table>
<tr><th>Indicators</th><th>P. M. 2.5</th><th>Total Energy consumption</th></tr>
<tr><td>No. of stops</td><td>

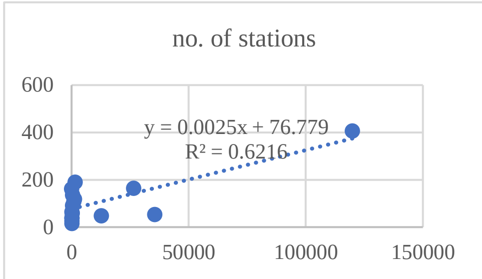
Figure 1: Regression and correlation Graphs between. no. of stop and pm value.</td><td>

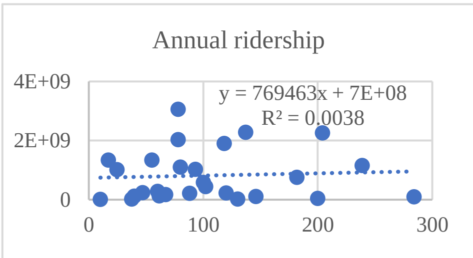
Figure 2:Regression and correlation Graphs between. no. of stops and energy</td></tr>
<tr><td>Annual Ridership</td><td>

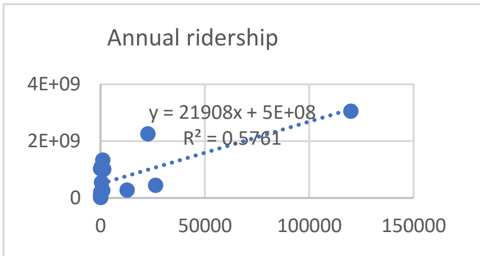
Figure 3: Regression and correlation Graphs between. annual ridership and pm</td><td>

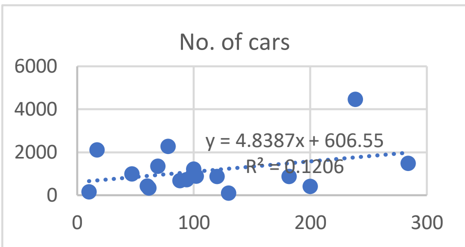
Figure 4: Regression and correlation Graphs between. annual ridership and energy</td></tr>
<tr><td>Number. of cars</td><td>

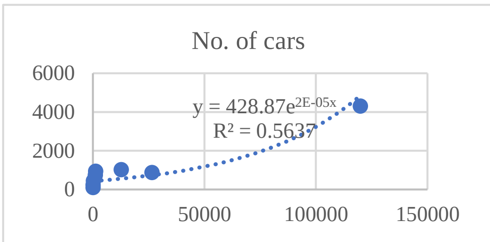
Figure 5:Regression and correlation Graphs between. no. of cars and pm</td><td>

Figure 6:Regression and correlation Graphs between. no. of cars and energy</td></tr>
</table>

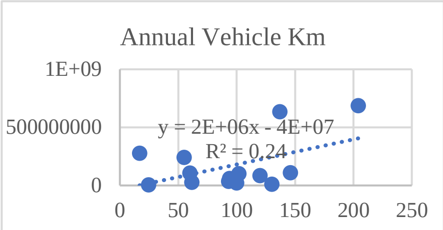
<table>
<tr>
<td>Annual vehicle-km</td>
<td>

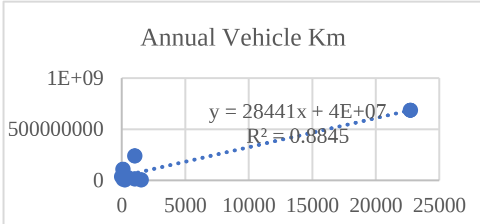
Figure 7:Regression and correlation Graphs between annual veh. Km and pm</td>
<td>

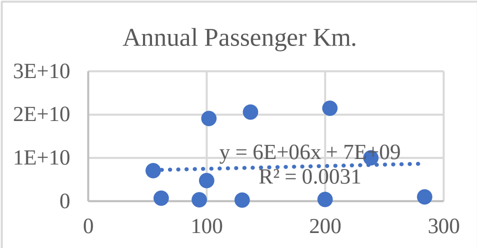
Figure 8:Regression and correlation Graphs between annual veh. Km. and energy</td>
</tr>
<tr>
<td>Annual Passenger-km</td>
<td>

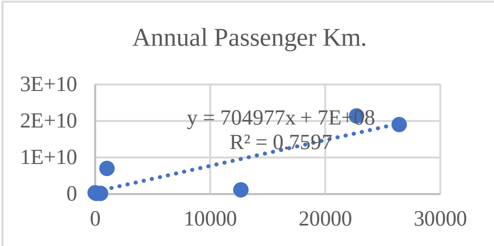
Figure 9: Regression and correlation Graphs between annual pass. Km and pm</td>
<td>

Figure 10: Regression and correlation Graphs between. Annual pass. km and energy</td>
</tr>
</table>

7. Benchmarking Metro Systems: Energy Efficiency and Air Quality Performance

7.1. Energy Performance Assessment

The metro systems were compared based on their total annual energy consumption (GWh). Total energy consumption is heavily dependent on the size of the metro system, the length of the network, and its patronage. This means that the results should be analyzed with respect to these parameters.

Table 3: Metro Systems with Lowest Total Energy Consumption (Absolute Values)

Rank	City	Country	Energy Use (GWh)	Key Practices
1	Sydney	Australia	84.13	Solar-powered, emission controls
2	Amsterdam	Netherlands	85.16	Regenerative braking, cycling integration
3	Copenhagen	Denmark	93.40	100% wind-powered trains
4	Los Angeles	USA	115.20	Small-scale, efficient network
5	Medellín	Colombia	126.39	Hybrid energy use

Table 4: Metro Systems with Highest Total Energy Consumption

Rank	City	Country	Energy Use (GWh)	Identified Issues
1	Tokyo	Japan	95,798	Fossil fuel reliance
2	Beijing	China	75,524	Coal-powered electricity
3	Barcelona	Spain	26,427	Aging infrastructure
4	Vancouver	Canada	22,720	High Operational Intensity

Table 3 presents metro systems with relatively low total energy consumption. These systems are generally smaller in scale, with shorter network lengths and lower operational demand. In contrast, Table 4 highlights metro systems with high total energy consumption, such as Tokyo and Beijing, where extensive infrastructure and high ridership contribute to increased energy requirements.

These observations indicate that total energy consumption reflects system scale rather than efficiency. Therefore, direct comparison between small and large metro systems based solely on absolute energy values may lead to misleading conclusions.

Note: Total energy consumption is influenced by system size and operational intensity; therefore, values are not directly indicative of energy efficiency. For more meaningful comparison, normalized indicators such as energy per passenger or per kilometer should be considered in future studies

7.2. Air Quality ($PM_{2.5}$) Performance

Metro systems were evaluated based on $PM_{2.5}$ concentration levels (µg/m³), where lower values indicate better indoor air quality.

Table 5: Metro Systems with Best Air Quality (Lowest $PM_{2.5}$)

Rank	City	Country	PM2.5 (µg/m³)	Contributing Factors
1	Sydney	Australia	10.1	Strict emission policies
2	Hong Kong	China	16.9	Green public transport policies
3	Singapore	Singapore	24.5	Air-purifying infrastructure
4	Jakarta	Indonesia	37.6	Low industrial emissions
5	Vancouver	Canada	39.7	Clean energy usage

The metros that have low levels of PM2.5 include Sydney, Hong Kong, and Singapore. The low levels of PM2.5 in such metros are due to their effective ventilation systems, cleaner energy sources, and environmental control.

Table 6: Metro Systems with Worst Air Quality (Highest $PM_{2.5}$)

Rank	City	Country	PM2.5 (µg/m³)	Major Pollution Sources
1	Chicago	USA	284.0	High vehicular emissions
2	London	UK	238.7	Industrial and traffic pollution
3	Beijing	China	204.0	Coal power and dust storms
4	New York	USA	200.0	Traffic congestion

Conversely, high PM2.5 levels can be witnessed in metros like Chicago, London, and Beijing. This is due to a combination of internal metro conditions and external urban pollution sources. In conclusion, these findings indicate that indoor air quality is influenced not only by operational factors, but also by external pollution levels, ventilation design, and maintenance practices.

7.3. Best Practices from High-Performing Systems

Table 7: Strategies for Energy Efficiency and Air Quality Improvement

City	Energy Efficiency Measures	Air Quality Measures
Sydney	Solar-powered stations	Zero-emission zones near metro hubs
Copenhagen	Wind-powered trains	Bike-friendly infrastructure
Singapore	Regenerative braking	Green tunnels with air filtration
Paris	20% energy recovery from braking	Ban on diesel trains in city center

Efficient urban rail transit systems utilize both technological and policy solutions. They consist of incorporating renewable energy sources, such as solar energy for power stations and wind energy for electric power generation, as well as regenerative braking techniques that help recapture energy through train operation. Advanced ventilation and filtration methods are employed in improving the indoor air quality. Efficient regulation mechanisms, such as emissions control policies, also help improve efficiency.

7.4. Areas for Improvement in Low-Performing Systems

Table 8: Improvement Strategies for Low-Performing Metros

City	Energy Issue	PM2.5 Issue	Recommended Actions
Tokyo	High fossil fuel use	78 µg/m³	Shift to renewables, regenerative tech
Barcelona	Aging infrastructure	102 µg/m³	Fleet upgrades, congestion pricing
Beijing	Coal power dependence	204 µg/m³	Solar farms, stricter emissions
LA	Low network coverage	130 µg/m³	System expansion, renewable microgrids

For instance, metro systems that use more energy or have bad air quality usually suffer from problems like heavy reliance on fossil fuel power plants, outdated technology, and high amounts of pollution from external factors. In other situations, lack of incorporation of advanced technologies can be another factor that leads to reduced efficiency.

7.5. Main Trends

Trends that have been established by the analysis are the following: first, there is a positive correlation between energy use and the scale and intensity of operation in metro systems, thus implying that large-scale systems have greater requirements for energy. Secondly, there is a weak correlation between the amount of $PM_{2.5}$ and operations-related factors, hence implying the importance of environment-related conditions.

7.6 Implications

It can therefore be concluded from the benchmarking findings that efforts to improve metro sustainability should adopt an integrated approach. On one hand, technological solutions such as energy efficiency technologies and regenerative braking need to be supported by policy initiatives including renewable energy use and air quality standards. On the other hand, proper management of environmental pollutants is critical.

8. Scenario Forecasting Using Monte Carlo Simulation

8.1 Methodology

The Monte Carlo method was used to determine possible future trends of energy consumption and $PM_{2.5}$ concentration in various cities under specific policy intervention strategies. In the simulation, uncertainty was captured by running the model 1,000 times with mean and standard deviation (μ and σ respectively) values extracted from the provided data set. To analyze, the impact of the policy interventions was considered on a percentage reduction basis. In this case, 15-25% reduction of energy consumption and $PM_{2.5}$ concentration were considered. These represent realistic figures observed in past studies dealing with renewable energy and energy efficiency policies.

The results from the simulation were presented in terms of probability distribution.

8.2 Key Findings

From the results obtained from the simulation exercise, there is a clear distinction in the performance of various metro systems in relation to variance and sustainability metrics. Starting with energy consumption, large metros such as Tokyo have high energy consumption rates and are highly variable (95,798 ± 3,449 GWh), implying that the system is sensitive to changes. The same is seen for Vancouver (22,720 ± 1,022 GWh) and its sensitivity to environmental factors. On the other hand, smaller metros such as Sydney (84.13 ± 2.4 GWh) and Amsterdam (85.16 ± 2.5 GWh) have constant energy rates. When comparing the $PM_{2.5}$ concentration, it is evident that cities such as Chicago (284.0 ± 8.2 µg/m³), London (238.7± 6.9 µg/m³), and Beijing (204.0 ± 5.9 µg/m³) have high levels of pollutants and remain constant. In addition, some metros such as Sydney (10.1± 0.3 µg/m³), Hong Kong, and Singapore have lower levels.

Regarding cities, there is an example of Beijing, where high energy demand and pollution coincide. At the same time, low $PM_{2.5}$ levels can be found in the system of Singapore despite relatively high energy demand, which is due to appropriate policies and technology use. Moreover, low energy demand can be observed in Copenhagen with relatively high levels of $PM_{2.5}$.

8.3 Policy Implications

The findings from the simulations are useful in giving insight into several matters. For cities with high volatility in their energy consumption, it would be useful for them to incorporate smart grids and use more renewable energies to ensure a stable flow of energy. In cases where there are high concentrations of $PM_{2.5}$, it is necessary to ensure emissions restrictions and good ventilation and filtration processes.

Singapore serves as an example of how pollution can be minimized even with high levels of intensity with proper policy enforcement and technological advancements.

8.4 Limitations

The study has been faced by several constraints. Availability of data has not been uniformed across all urban centers, where some cities such as Hong Kong and Delhi have not had complete datasets while other cities like Vienna and Milan lack $PM_{2.5}$ data. Another issue with the study is the assumption that a reduction range between 15–25% can be used, since actual results may differ from one place to another.

9. Strategy Development for Sustainable Metro Systems

9.1 Key Recommendations

Based on the analysis and findings from simulations, some measures that can be used to enhance the sustainability of metro services have been outlined below.

Operational Measures

- Implementation of real-time scheduling that would enable proper management of the frequency of metro operation, hence avoiding wastage of energy
- Operator training in energy-efficient driving techniques

Technical Solutions

- Installation of regenerative brakes in metro vehicles
- Utilization of alternative energy sources such as solar energy by incorporation of solar panels

Policing Measures

- Setting realistic targets for reduction of $PM_{2.5}$ concentrations
- Creation of public education campaigns regarding the use of sustainable means of transport

9.2 Implementation Framework

To guarantee its applicability, a staged implementation strategy is necessary.

- Near-term: Piloting of energy-efficient innovations and practices
- Medium-term: Expansion of proven measures and incorporation into system design
- Long-term: Ongoing evaluation and optimization of energy consumption and air quality

It is vital for the collaboration among transit agencies, universities, and the industry to drive innovations and facilitate implementation.

10. Comprehensive Summary and Conclusions

In this study, a comparative analysis is carried out involving 47 metro systems operating in different parts of the world, with a focus on the connection between operational parameters, energy use, and indoor $PM_{2.5}$ levels. The analysis uses correlation, regression models, and Monte Carlo simulation to determine the factors influencing performance and suggest sustainable pathways for metro operations.

10.1 Key Findings

Energy Consumption:

The findings reveal a robust positive correlation between the levels of energy consumption and various operational parameters. Among these, the number of trains in the fleet (r = 0.974) and the distance traveled by vehicles (r = 0.940) have the highest correlations with overall energy consumption. The regression analysis shows that the number of trains in the fleet is the most significant predictor ($R^2 = 0.949$). The large urban metro systems, such as the one in Tokyo, consume relatively higher amounts of total energy (≈95,799 GWh). On the other hand, the smaller metro systems, such as Sydney's, consume much less total energy (≈84.1 GWh) because of their reduced sizes. Therefore, it can be concluded that total energy consumption largely depends on the size of the system and should not be taken alone as an indicator of its efficiency.

Air Quality ($PM_{2.5}$):

The relationship between $PM_{2.5}$ and operational parameters appears to be less correlated and inconsistent. However, a moderate correlation exists with respect to system scale, e.g., number of lines (r = 0.496). Thus, it can be deduced that there are more factors influencing air quality. Lower levels of $PM_{2.5}$ have been detected in systems like Sydney (10.1 µg/m³), while extremely high levels have been detected in urban areas like Chicago (284 µg/m³). Systems like Beijing and Barcelona have higher $PM_{2.5}$ levels, which might warrant a special intervention.

Case Studies:

Some examples include case studies that indicate the impact of policy and technology on enhancing system performance, where Santiago has recorded significant improvements because of using renewable energy sources, while in the case of Singapore, $PM_{2.5}$ concentrations remains low (≈24.5 µg/m³) despite high intensity of operations.

Simulation Insights:

As per Monte Carlo simulation outcomes, it is found that big metro systems like Tokyo have high variability in their energy use (σ ≈ ±3,449 GWh). In contrast, small metro systems like Sydney are relatively stable when it comes to air quality (σ ≈ ±0.29 µg/m³). On the other hand, according to scenario analysis, it is possible to decrease energy consumption by up to 25% and decrease $PM_{2.5}$ emissions by 30–40%.

10.2 Strategic Framework

The results have indicated that the development of a multi-faceted plan is necessary to improve sustainability of metro systems.

1. Operational Improvement
   - Adoption of dynamic scheduling to match services according to demand
   - Conducting training to encourage energy-saving operations
   - Adopting regenerative braking technology
2. Technology
   - Renewable energies, such as solar and wind power plants
   - Ventilation and filtration technology for better indoor air quality
3. Policy Interventions
   - Setting of achievable emissions and air quality goals
   - Encouragement of mode shift through public education and financial motivation
   - Use of green purchasing policies and sustainable criteria
4. Phased Implementation
   - Immediate actions (0–2 years): Optimization and pilot projects
   - Intermediate steps (2–5 years): Application of technology and policy formulation
   - Long-term plans (5–10 years): Comprehensive implementation and ongoing evaluation

10.3. Conclusions and Future Directions

From this study, it can be clearly seen that metro system energy consumption depends mostly on the size and intensity of their operations. As for $PM_{2.5}$ concentrations, these are defined not only by the features of the metro system but also by the state of the environment around. Despite providing valuable data, there are some shortcomings which must be noted. For instance, access to information varies in different places, including those where the number of data samples is very low, like some parts of Africa. Moreover, distinguishing the exact sources

of $PM_{2.5}$ in metro environment is quite difficult, and the simulations used have some uncertainty due to assumptions made for scenarios. In order to address these issues in future research, one may consider increasing the volume of data in developing countries and utilizing innovative methods, including artificial intelligence systems for energy management and evaluations of the impacts of various sustainability initiatives.
Finally, it is worth mentioning that conducting cost-benefit analyses may facilitate decision-making.

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Appendix A: Metro Systems Included in the Study

Region	Cities Included
Europe	Berlin, Brussels, Vienna, Prague, Copenhagen, Paris, Budapest, Milan, Amsterdam, Oslo, Warsaw, Lisbon, Barcelona, Stockholm, London, Istanbul, Madrid, Rome
Americas	New York, Los Angeles, Chicago, New Jersey (PATH), Toronto, Montreal, Vancouver, Mexico City, São Paulo, Rio de Janeiro, Buenos Aires, Medellín, Santiago, Washington D.C.
Asia & Middle East	Tokyo, Yokohama, Saitama, Beijing, Shanghai, Delhi, Bangalore, Singapore, Hong Kong, Jakarta, Taipei, Dubai
Africa	Cairo
Australia	Melbourne, Sydney

A total of 47 metropolitan areas is included in the study. Cities with multiple metro operators are considered as a single system. The selection ensures geographic diversity and is based on data availability for energy consumption and $PM_{2.5}$ indicators,