

Harmonizing eco-friendly transport system: A blueprint for addressing energy consumption and environmental impact in Benin

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ABSTRACT

This study uses economic and ecological parameters to examine the trends in energy consumption and environmental degradation in Benin's transport sector. With growing economic growth, Benin is confronted with increased greenhouse gas emissions and pollution from road transport. The study thus assesses the nexus between CO₂ emissions, energy use, industry, and economic growth in Benin's transport context using data from 1990 to 2020. Using econometric models such as the Autoregressive Distributed Lag (ARDL) bounds test and Maki's cointegration test, the study was based on significant long-run interactions between those variables. It also established energy consumption and industrial expansion as substantial contributors to CO₂. The study findings, therefore, established that these emissions were directly proportional to the rise in the GDP. The results also showed that infrastructure and capital investment could contribute to lower levels of these emissions over time. The following specific policy framework will balance economic development with environmental protection by encouraging green investment, efficient use of energy, and renewable energy. Emphasis on electric vehicles, improved public transport, and urban planning can align Benin with sustainability goals. Similarly, the principles of sustainable development applicable to Benin's transport sector include the 'polluter pays' principle, inter-generational equity, and the adoption of clean technologies. Measures include mandatory emissions testing for vehicles, investment in e-mobility infrastructure, and integrating lifecycle analysis in transport project planning. Thus, this work contributes to an informed level of sustainable urban planning and provides the policy framework within which energy challenges are responded to in the context of economic growth.

1. Introduction

The global environment faces unprecedented challenges due to human activities, particularly energy consumption in the transportation sector (Martinez-Zarzoso, 2008). According to Lamb and DiLorenzo (2014), urbanization has experienced significant acceleration since 1950 on a global scale. Environmental issues have sparked great interest within the scientific community and concern governments worldwide (Sotamenou and Nguemdjio, 2019). Indeed, the main threat facing humanity is the destruction of the ozone layer due to greenhouse gas emissions, particularly carbon dioxide (CO₂). According to Stern's estimates (2007), this threat could result in economic losses of up to \$550 billion if concrete measures are not taken. According to Chakamera and Alagidede (2018), on the environmental front, the sub-Saharan Africa

region continually faces alarming levels of energy poverty, inefficiency, and negative externalities resulting from climate change. This reflects the region's lack of attention to its environmental concerns. Its energy crises are attributed to increased CO₂ emissions from electricity and heat production (Burhama Eka, 2023) and energy consumption (Roques and Roux, 2018; Gazull, 2018). However, the ECOWAS, particularly Benin, is not exempt. Due to the increasing use of energy, carbon dioxide emissions have experienced a significant increase over the last century, directly impacting economic growth and financial development (Ouerghi and Tej, 2021; Sadorsky, 2011). Thus, the relationship between CO₂ emissions, industrial and manufacturing sector growth, energy consumption, capital formation, and economic growth is central to current financial issues.

In Benin, the issue of energy consumption in transportation (road

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and air) presents a crucial point of reflection, given the extent of urbanization, population growth, and economic development. The impact of transportation on the environment is significant, ranging from air pollution to ecosystem degradation, thus posing a major challenge for a country seeking to reconcile economic development and environmental preservation. Transportation, as a fundamental driver of economic vitality, is inherently intertwined with the consumption of non-renewable energy, thus contributing to the exacerbation of greenhouse gas emissions and other forms of environmental pollution (Luc, 2023). The transportation sector is widely recognized as one of the primary sources of CO₂ emissions and atmospheric pollutants, playing a paramount role in climate change and the deterioration of air quality.

In this context, a comprehensive exploration of the correlation between energy consumption in the transportation sector and environmental degradation in Benin assumes crucial significance. It is imperative to comprehend how the evolving transportation demand, energy choices, and mobility policies impact the environment. This analysis adopts a holistic perspective, encompassing factors such as manufacturing value-added, economic growth, financial development within the lens of gross capital and infrastructure formation, energy consumption, and the implications of these choices on environmental quality (Bekhet et al., 2017; Kasman and Duman, 2015; Sadorsky, 2014; Saboori and Sulaiman, 2012; Bloch et al., 2012).

Benin's rapid urbanization and population growth have increased mobility demand, particularly in public and private transportation. Economic growth and the expansion of manufacturing activities in the country are also key factors driving this increased energy demand (Onsomu et al., 2023). Concurrently, financial development and capital investments are vital in modernizing transport infrastructure and promoting cleaner technologies (Shahbaz et al., 2012; Zeng et Eastin, 2012). In this evolving environment, it is essential to understand how energy consumption in transportation interacts with these economic and environmental variables. Benin has also committed to promoting renewable energy to reduce its dependence on fossil fuels, making renewable energy consumption in the transportation sector even more relevant.

This study aims to provide a comprehensive understanding of the complex links between energy consumption in transportation and its impact on the environment in Benin. By examining these interactions and identifying potential action levers, it seeks to provide a solid foundation for developing sustainable policies to mitigate the adverse impacts of transportation on the environment while promoting balanced economic development that respects environmental imperatives.

This article will be organized into six sections to achieve this objective, including the introduction. The following sections will present a literature review in section two. Section three will focus on the adopted methodology. The presentation of results discussion will be covered in sections four and five, and conclusions, policy directions, limitations, and future research direction will be in section six, respectively.

2. Literature review

Transportation means are significant energy consumers, with a rising trend, unlike other sectors. This observation mainly stems from the growth of road transportation, which is characterized by lower energy efficiency compared to air and rail transportation, while being more polluting. The current debate on climate change and ozone layer depletion sheds light on energy expenditures and the crucial question of the sustainability of current lifestyles and consumption habits in the face of disastrous ecological consequences. There is abundant literature that addresses the causal relationship between energy consumption, urbanization, economic growth, financial development, foreign direct investment, renewable energy consumption, non-renewable energy consumption, and carbon emissions, as evidenced by the works of Mahalik et al. (2017), Bekhet et al. (2017), Nnaemeka et al. (2016), Kuo

et al. (2014), Olatunji et al. (2014), Panayotou (1997), and Grossman et Krueger (1995).

Referring to the environmental Kuznets curve (EKC), Grossman and Krueger (1995) assert that economic growth hurts the environment until individuals become aware of this issue and adopt ethical behaviors. According to the environmental Kuznets curve hypothesis, a positive relationship exists between energy consumption and income, followed by a decline once income reaches a certain threshold. The overall impact of economic growth on energy consumption depends on the predominance of the most significant effect among scale, technique, and composition effects (Copeland and Taylor, 2004).

According to Keho's research (2016), the impact of foreign direct investment (FDI) on the energy sector depends on disparities in factor endowments and environmental policies. Therefore, foreign direct investments can lead to either a decrease or an increase in energy consumption, depending on the country's comparative advantage in polluting or non-polluting industries. According to Rafitoson (2017), an energy source is considered non-renewable from declining reserves, including fossil biofuels such as coal, gas, and oil, as well as nuclear energy. In contrast, renewable energy is derived from sources constantly replenished by nature. Therefore, renewable resources regenerate at a rate higher than our consumption rate and do not deplete.

Studies, including those by Cadot et al. (2015), have examined the relationship between manufacturing value added and energy consumption in transportation, highlighting the importance of manufacturing activities in energy dynamics. The relationship between population density, land use, and energy consumption has been studied by Poumanyong and Kaneko (2010) and Sadorsky (2014), emphasizing how specific urbanization patterns can influence transportation patterns and associated energy demand. Population growth combined with urbanization leads to an increase in energy demand within urban areas. However, intensive energy use can result in significant CO₂ emissions and environmental degradation (Halicioglu, 2009). It should be noted that rapid urbanization can have notable repercussions on economic growth, energy consumption, and environmental degradation in developing countries (Kasman and Duman, 2015; Acaravci and Ozturk, 2010; Martinez-Zarzoso, 2008). Similarly, it is essential to note that increased energy consumption can lead to intensified economic activity and increased CO₂ emissions.

Once the theoretical developments have been presented, it is crucial to present empirical analyses. The results are generally subject to the influence of several factors, such as the study period, the level of development of the economies under study, the econometric techniques used, sample homogeneity, and the consideration of control variables. For example, in a study conducted by Shafik (1994) on a panel of 149 countries between 1960 and 1990, a positive correlation was found between gross domestic product (GDP) and CO₂ emissions. However, Holtz-Eakin and Selden (1995) did not observe a break in this positive correlation in their study on a panel of 131 countries between 1951 and 1986, thus confirming the theory of the Environmental Kuznets Curve (EKC). However, It should be noted that the latter's turning point is high (\$35,428). These results are consistent with those obtained by Cole et al. (1997) regarding CO₂ emissions. During the period from 1990 to 2015, Balogan (2021) undertook a comprehensive assessment of the impact of various factors, such as energy consumption in the transportation sector, foreign direct investment (FDI), economic growth, and urbanization on carbon dioxide (CO₂) emissions within the member countries of the West African Economic and Monetary Union (WAEMU). The main objective of this study was also to verify the validity of the environmental Kuznets curve (EKC) hypothesis. Using advanced methods such as cointegration approaches developed by Pedroni (1999) and Kao (1999), the results revealed a close and significant relationship between energy consumption in the transportation sector, FDI, urbanization, economic growth, and CO₂ emission levels within WAEMU countries. Furthermore, long-term estimates conducted through PMG models demonstrated the significant influence exerted by these variables on CO₂ emissions.

The study conducted by [Adom et al. \(2012\)](#) employed the ARDL approach to examine electricity demand in Ghana. The results highlight that income, industrial growth, and urbanization play a determining role in energy consumption in this country. Similarly, [Shahbaz and et Lean \(2012\)](#) analyzed the correlation between Tunisia's energy consumption, financial development, economic growth, industrialization, and urbanization. The conclusions of this study revealed a long-term positive relationship between financial development, industrialization, urbanization, and energy consumption. Furthermore, [Poumanyong and Kaneko \(2010\)](#) studied the impact of urbanization on CO₂ emissions in a panel of 99 countries over the period 1975–2005. Using various models, they found that urbanization decreases energy consumption in low-income countries, but increases in middle and high-income countries. Urbanization contributes to an increase in CO₂ emissions across all income types.

In a study by [Ouerghi and Tej \(2021\)](#), the link between financial development, economic growth, and energy consumption in Tunisia was examined from 1980 to 2014. Using the autoregressive ARDL model and the [Toda and Yamamoto \(1995\)](#) approach allowed for testing causality. The results highlight an indirect relationship between energy consumption and economic growth, emphasizing the importance of energy for business and investment activities. Similarly, [Gaies et al. \(2019\)](#) analyzed the link between financial development and energy consumption in most MENA countries from 1996 to 2014 using a linear and nonlinear dynamic panel. The results show a significant positive correlation between the size and intermediation capacity of the banking system and energy consumption, as well as an inverted U-shaped relationship between financial development and energy demand. Finally, [Shahbaz et al. \(2016\)](#) studied the long-term relationship between economic growth, financial development, and energy consumption in India using the ARDL method and [Bayer and Hanck \(2013\)](#) cointegration test. Their results suggest that financial development can ultimately lead to reduced energy consumption.

The work of [Kiribou et al. \(2025\)](#) on Burkina Faso provides a methodological precedent in estimating fuel demand and greenhouse gas emission factors under the IPCC guidelines, reinforcing the importance of data-driven urban mobility planning. [Osei et al. \(2025\)](#) illustrate how Ghana is leveraging autogas as a decarbonization strategy, which offers a useful point of comparison to Benin's renewable energy potential. Additionally, [Maji and Adamu \(2021\)](#) reveal that in Nigeria, renewable energy consumption positively impacts the environmental quality of the transport sector, highlighting regional opportunities for scaling clean energy transitions. These comparisons not only contextualize Benin's challenges within a broader regional framework but also enrich the policy discourse by pointing to shared lessons and scalable innovations. According to the findings of the [TEST study \(1991\)](#), which is based on in-depth research on energy consumption, considering all factors, the amount of energy used to propel a vehicle sometimes represents only 62 % of the total energy consumption. It is also worth noting that road and rail infrastructure construction and maintenance also result in energy consumption. Road infrastructure consumes 2.42 times more energy per kilometer per year than its rail counterpart.

Based on the literature mentioned in the earlier review, it is justified to empirically analyze the link between CO₂ emissions, energy consumption, urbanization, financial development, FDI, renewable energy consumption, and non-renewable energy consumption in the context of Benin. Furthermore, the results of the studies are inconclusive and mixed. Additionally, to our knowledge, no study has examined the effects of energy consumption on transportation and environmental degradation in Benin. Therefore, this study fills this gap.

3. Data, model, and econometric methodology

This paper investigates the impact of gross domestic product (GDP), gross fixed capital formation (GFC), manufacturing value added (MVA), and energy consumption in the transport sector (TRA) on CO₂ emissions

in Benin for the period between 1990 and 2020. [Table 1](#) presents the variables and data sources.

In this context, the referenced mathematical function is as in Eq. (1):

$$\ln\text{CO}_2 = f(\ln\text{GDP}, \ln\text{GFC}, \ln\text{MVA}, \ln\text{TRA}) \quad (1)$$

Mathematical models are deterministic due to the absence of an error term. Our econometric model, including the error term, is as follows.

$$\text{LNCO}_2 = \beta_0 + \beta_1 \text{LN GDP}_t + \beta_2 \text{LNGFC}_t + \beta_3 \text{LNMVA}_t + \beta_4 \text{LNTRA}_t + \varepsilon_t \quad (2)$$

In Eq. (5), CO₂ represents carbon dioxide emissions (kt); GDP represents gross domestic product (constant 2015 current US\$); MVA represents industrialization (manufacturing value added as a percentage of GDP); and TRA represents total final energy consumption by the transport sector (terajoules). LN indicates that the logarithms of the variables are taken. Therefore, we could say that our econometric model is based on a log-log model. Additionally, β_0 indicates the constant term while ε_t denotes the error term. $\beta_1, \beta_2, \beta_3, \beta_4$ indicate slope parameters or flexibility values of variables.

This study used unit root tests with and without a structural break for stationarity analysis. First, we employ the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests without a structural break.

[Maki \(2012\)](#), on the other hand, developed the cointegration test in which the time of the break is determined endogenously to allow up to five breaks. The equations of the [Maki \(2012\)](#) model are as follows:

$$\text{Model 0 : } y_t = \mu + \sum_{i=1}^k \mu_i D_{i,t} + \beta' x_t + u_t, \quad (3)$$

$$\text{Model 1 : } y_t = \mu + \sum_{i=1}^k \mu_i D_{i,t} + \beta' x_t + \sum_{i=1}^k \beta_i' x_t D_{i,t} + u_t, \quad (4)$$

$$\text{Model 2 : } y_t = \mu + \sum_{i=1}^k \mu_i D_{i,t} + \gamma t + \beta' x_t + \sum_{i=1}^k \beta_i' x_t D_{i,t} + u_t, \quad (5)$$

$$\text{Model 3 : } y_t = \mu + \sum_{i=1}^k \mu_i D_{i,t} + \gamma t + \sum_{i=1}^k \gamma_i t D_{i,t} + \beta' x_t + \sum_{i=1}^k \beta_i' x_t D_{i,t} + u_t \quad (6)$$

Eq. (3) is the level shift model. Eq. (4), called the regime shift model, allows for structural breaks in β in addition to μ . Eq. (5) is model (4) with a trend. Eq. (6) represents structural breaks in levels, trends and regressors. Here $D_{i,t} (i = 1, \dots, k)$ denotes dummy variables and takes the value 1 when $t > TBi$, and takes the value 0 in other cases. TBi indicates the structural break period ([Maki, 2012; 2013](#)).

In the advanced stage of our study, we used the ARDL bounds test to analyze the long and short-run relationships of the variables. The ARDL bounds test is applied for variables with different degrees of integration (stationarity) and is considered a more effective model than other

Table 1
Variables and data sources.

Variable	Definition	Sources
CO2	CO2 emissions (kiloton)	WDI database
GDP	Gross Domestic Product (current US\$)	WDI database
MVA	Manufacturing value added (current US\$)	WDI database
GFC	Gross fixed capital formation (current US\$)	WDI database
TRA	Total final energy consumption by the transport sector (Terajoules)	www.iea.org

Note. The period of the data is from 1990 to 2020.

cointegration analyses (Pesaran and Shin, 1995; Pesaran et al., 2001). The bounds test is estimated before moving on to the analysis of the long-run and short-run coefficients. Depending on the results of the test, the ARDL procedure is applied. For the bounds test, an unconstrained error correction model is first built. The model in question, built on the basis of equation (7), is as follows.

$$\begin{aligned} \Delta LNCO2_t = & a_0 + \sum_{i=1}^m a_1 \Delta LNCO2_{t-i} + \sum_{i=0}^n a_1 \Delta LNGDP_{t-i} \\ & + \sum_{i=0}^p a_2 \Delta LNGFC_{t-i} + \sum_{i=0}^s a_3 \Delta LNMVA_{t-i} + \sum_{i=0}^y a_4 \Delta LNTRA_{t-i} \\ & + \varphi_1 LNGDP_{t-1} + \varphi_2 LNGFC_{t-1} + \varphi_3 LNMVA_{t-1} + \varphi_4 LNTRA_{t-1} + u_t \end{aligned} \quad (7)$$

In Eq. (7), a_0 symbolizes the constant term, while Δ denotes the difference operator, and u_t indicates the error term, respectively. The null and alternative hypotheses regarding the ARDL bounds test are presented below.

H0. $\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = 0$ (There is no cointegration relationship between the series)

H1. $\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 \neq 0$ (There is a cointegration relationship between the series)

The optimal number of lags and their compatibility with the stability assumptions will indicate whether or not the tests in question can be used. The equation for the short-run error correction model (ECM), built based on the ARDL model, taking into account equation (7) in the last step of the bounds test, is given below.

$$\begin{aligned} \Delta LNCO2_t = & a_0 + \sum_{i=1}^m a_1 \Delta LNCO2_{t-i} + \sum_{i=0}^n a_2 \Delta LNGDP_{t-i} \\ & + \sum_{i=0}^p a_3 \Delta LNGFC_{t-i} + \sum_{i=0}^s a_4 \Delta LNMVA_{t-i} \\ & + \sum_{i=0}^y a_5 \Delta LNTRA_{t-i} + \varphi_1 ECM_{t-1} + u_t \end{aligned} \quad (8)$$

In equation (8), the error correction term is given with a lag period by ECM_{t-1} , and φ_1 denotes the error correction parameter. The fact that the coefficient of ECM_{t-1} is statistically significant and has a negative sign that any long-run disequilibrium between the dependent variable and a set of independent variables will converge to the long-run equilibrium association. Then, we employed the fully modified ordinary least squares (FMOLS) proposed by Phillips and Hansen (1990), dynamic ordinary least squares (DOLS) introduced by Stock and Watson (1993), and CCR methods proposed by Park (1992) for long-run estimation tests. Following that, we applied the dynamic simulated ARDL (DARDL) model proposed by Jordan and Philips (2018) and kernel-based regularized least-squares (KRLS) introduced by Hainmueller and Hazlett

(2014) and Ferwerda et al. (2017). Finally, we performed a Bootstrap-based symmetric causality analysis proposed by Hacker and Hatemi-J (2006), which does not consider the stationarity levels of the variables.

4. Empirical findings

Table 2 presents descriptive statistics of the variables. Accordingly, it was determined that the standard deviation of the variables was high. The logarithm of the variables was taken to reduce the series' scale difference and eliminate the heteroscedasticity problem.

The results of the unit root tests in Table 3 indicate that all variables are stationary when the first difference is taken for the constant model. In the constant and trend model, while the variable LNGFC is stationary at level, i.e., I(0), the other variables become stationary when their first difference is taken, I(1). However, the results of Lee and Strazicich (2003) unit root test considering structural breaks in Table 4 illustrate variables have a mixed integration level. In other words, the degrees of stationarity are mixed in the constant and trend models. Therefore, we applied the structural break cointegration test of Maki (2012), the ARDL bounds test approach developed by Pesaran et al. (2001), dynamic ARDL simulations (DARDL), and Kernel-based regularized least squares (KRLS) introduced by (Hainmueller and Hazlett, 2014). to obtain reliable estimation results. The ARDL bounds test is applied to variables with different degrees of integration (stationarity) and is said to be a more effective model than other cointegration analyses (Pesaran et al., 2001). While Maki's (2012) cointegration analysis with structural breaks produces effective results when the stationarity levels of the variables are I(1) and I(1), the ARDL bounds test allows the production of meaningful results when the stationarity levels of the variables are I(1) and I(0). At the same time, this test also examines small samples (Kamaruddin and Jusoff, 2009).

Table 5 presents the results of the structural break cointegration test according to Maki (2012). According to the results, there is a long-run cointegration relationship between the variables in Model 0 and Model 2. However, the ARDL (4, 3, 4, 2, 3) bounds test results in Table 6 indicate that the F-statistic values are more significant than the critical value. This result denotes that the null hypothesis of no long-run cointegration relationship is rejected. In other words, it proves a long-run cointegration relationship between the variables. The structural break dates where the results were statistically significant were determined as 1998, 2001, 2005, and 2010.

The long-run and short-run coefficient estimation results of the established ARDL model are presented in Table 7. Looking at the long-term coefficients, a 1 % increase in LNGDP raises LNCO₂ by 1.07 %, while a 1 % increase in LNGFC reduces LNCO₂ by 0.46 %, with other things being constant. Furthermore, other things being constant, a 1 % increase in LNMVA raises LNCO₂ by 0.34 %, while a 1 % increase in LNTRA raises LNCO₂ by 0.62 %.

Table 2
Descriptive statistics of the variables.

	CO ₂ emissions (kt)	Gross domestic product (current US\$)	Gross fixed capital formation (current US\$)	Manufacturing, value added (current US\$)	Total final energy consumption by transport sector (Terajoules)
Codes	CO2	GDP	GFC	MVA	TRA
Mean	3281.202	8.11E+09	1.42E+09	8.12E+08	33378.06
Median	2899.6	7.53E+09	9.96E+08	1.03E+09	21911
Maximum	7980.4	1.47E+10	3.95E+09	1.52E+09	94878
Minimum	273.51	3.96E+09	2.27E+08	1.29E+08	1617
Std. Dev.	2457.686	3.13E+09	1.13E+09	4.89E+08	29623.47
Skewness	0.382017	0.511832	0.822028	-0.28695	0.703047
Kurtosis	1.971037	2.232321	2.527196	1.4737	2.232553
Jarque-Bera	2.121581	2.114741	3.780016	3.434478	3.314515
Probability	0.346182	0.347368	0.151071	0.179561	0.190661
Sum	101717.3	2.51E+11	4.40E+10	2.52E+10	1034720
Sum Sq.Dev.	1.81E+08	2.94E+20	3.83E+19	7.18E+18	2.63E+10
Observations	31	31	31	31	31

Table 3

The results of the ADF and PP unit root tests.

	ADF				PP			
	C		C + T		C		C + T	
	t-Stat.	Prob.	t-Stat.	Prob.	t-Stat.	Prob.	t-Stat.	Prob.
LNCO2	-1.15	0.68	-1.51	0.80	-1.20	0.66	-1.50	0.81
LNGDP	-0.06	0.96	-2.52	0.32	-1.35	1.00	-2.02	0.57
LNGFC	-1.58	0.48	-4.66***	0.00	-0.24	0.92	-4.63***	0.00
LNMA	-1.24	0.64	-1.14	0.90	-1.25	0.64	-1.03	0.92
LNTRA	-1.01	0.74	-1.55	0.79	-1.02	0.73	-1.55	0.79
ΔLNCO2	-4.75***	0.00	-4.35**	0.01	-4.76***	0.00	-9.29***	0.00
ΔLNGDP	-4.06***	0.00	-3.98**	0.02	-5.86***	0.00	-5.88***	0.00
ΔLNGFC	-6.53***	0.00	-3.89**	0.03	-13.6***	0.00	-14.0***	0.00
ΔLNMA	-6.23***	0.00	-6.39***	0.00	-6.18***	0.00	-6.42***	0.00
ΔLNTRA	-4.79***	0.00	-4.86***	0.00	-4.77***	0.00	-5.88***	0.00

Notes. While we used the Schwarz information criterion for the ADF test, the maximum lag length was chosen to be six. For the PP test, the bandwidth was analyzed using the Newey-West Based Bartel Kernel technique. *, **, and *** denote the significance level at the 10 %, 5 %, and 1 %, respectively.

Table 4

The results of Lee and Strazicich(2003) unit root test.

Variable	Model	Lags	Break Dates	Test Statistics
LNCO2	A	1	1995; 1997	-2.96
	C	2	1995; 2002	-5.94**
LNGDP	A	1	2005; 2009	-3.71*
	C	2	2000; 2010	-5.77**
LNGFC	A	0	1998; 2015	-4.94*
	C	2	1998; 2016	-6.93***
LNGFC	A	0	1999; 2003	-2.16
	C	0	1997; 2005	-4.91
LNTRA	A	1	1995; 1997	-3.83*
	C	2	1995; 2001	-8.15***

Notes. *, **, and *** denote the significance level at the 10 %, 5 %, and 1 %, respectively.

Table 5

Maki (2012) cointegration test results with multiple breaks.

	Model 0	Model 1	Model 2	Model 3
	(Level shift)	(Level shift with trend)	(Regime shifts)	(Trend and Regime shifts)
Test statistics, and structural break dates	-5.25* (1998) (2001) (2010)	-4.79 (2002) (2007) (2017)	-6.99** (2005) (2010)	-5.14 (2010)

Notes. Structural break dates are indicated in parentheses. For critical values, Maki (2012) paper was taken as reference. *, and ** indicate significance level at 5 %, and 10 %.

Table 6

The results of ARDL (4, 3, 4, 2, 3) bounds test.

Cointegration hypotheses	F-statistics	Lower I (0)	Upper I (1)
Carbon model			
lnCO ₂ = f(lnGDP, lnGFC, lnMVA, lnTRA)	8.106***	10 % 2.75 5 % 3.35 1 % 4.76	3.99 4.77 6.67

Notes. *** indicates a significance level of 1 %.

As for the short-term estimation results, it is found that a 1 % increase in the 1-lag value of LNCO₂ raises LNCO₂ in the current period by 0.76 %, while a 1 % increase in the 2-lag value of LNCO₂ raises LNCO₂ in the current period by 0.36 %, other things being constant. Moreover, other factors are constant; a 1 % increase in LNGFC increases LNCO₂ by 0.14 %, while a 1 % increase in LNMA raises LNCO₂ by 0.10 %. Finally, a 1 % increase in LNTRA raises LNCO₂ by 0.74 %. It can be seen that the

Table 7

The results of the ARDL long and short-term estimates.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Long-run estimates:				
LNGDP	1.07**	0.30	3.56	0.01
LNGFC	-0.46**	0.16	-2.93	0.03
LNMA	0.34***	0.03	10.45	0.00
LNTRA	0.62***	0.04	15.20	0.00
Short-run estimates:				
ΔLNCO2(-1)	0.76***	0.11	7.09	0.00
ΔLNCO2(-2)	0.36***	0.08	4.65	0.00
ΔLNGDP	0.38	0.39	0.98	0.37
ΔLNGFC	0.14**	0.05	2.91	0.03
ΔLNMA	0.10*	0.05	2.04	0.09
ΔLNTRA	0.74***	0.01	50.12	0.00
ECM(-1)	-0.94***	0.11	-8.22	0.00
No. of Obs.	31.00			
R-squared	0.99			
F-statistics	2855.7***			
Bounds test (F-stat)	8.106***			
Selected ARDL model	ARDL(4, 3, 4, 2, 3)			

Notes. HAC standard errors & covariances was applied in the analysis process (Barlett kernel, Newey-West fixed bandwidth = 4000 t-statistics) for robust estimators. *, **, and *** denote the significance level at the 10 %, 5 %, and 1 %, respectively.

error correction model (ECM) is statistically significant and takes values between 0 and -1. In other words, short-term analysis results are valid.

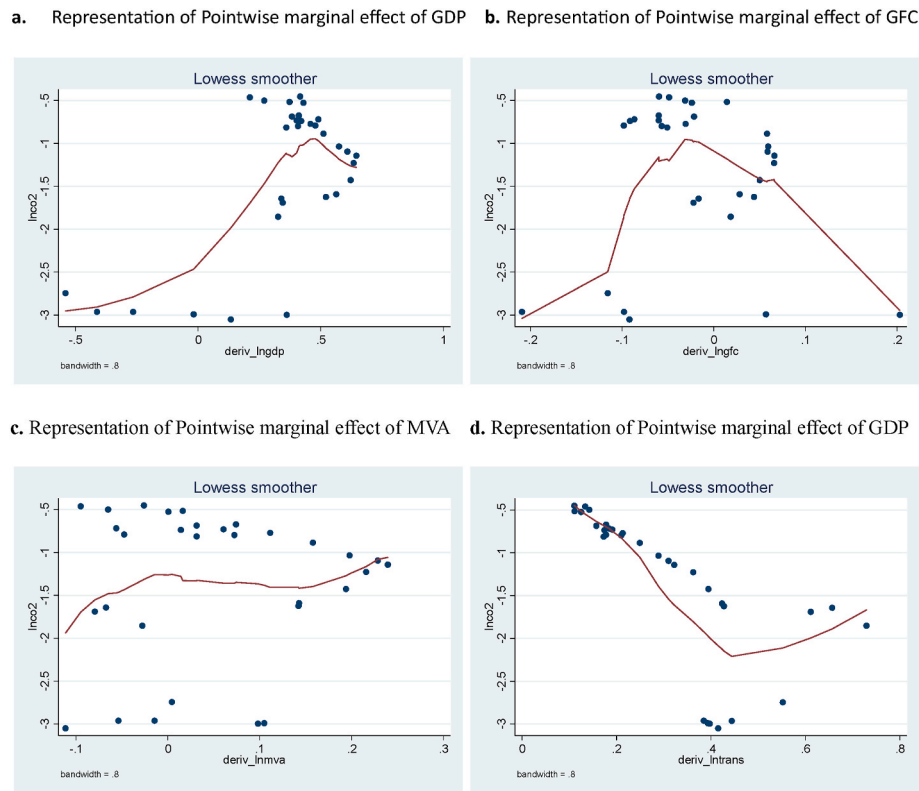
Diagnostic test results are presented in Table 8 (see Fig. 1). Accordingly, the null hypothesis stating that there is no autocorrelation and heteroscedasticity problem is accepted according to the test statistics. The assumption of normality is also provided. Additionally, Cusum and Cusum of squares test results have been stable (see Graph 2).

Additionally, in Table 9, Panel A indicates the DARDL results, while Panel B illustrates the KRLS results. The results of the DARDL estimation show that, ceteris paribus, a 1 % increase in lnGDP leads to a 0.48 % rise in lnCO₂ in the long run, while a 1 % increase in lnMVA leads to a 0.145 % fall in lnCO₂. In the short run, a 1 % increase in lnTRA boosts lnCO₂ by

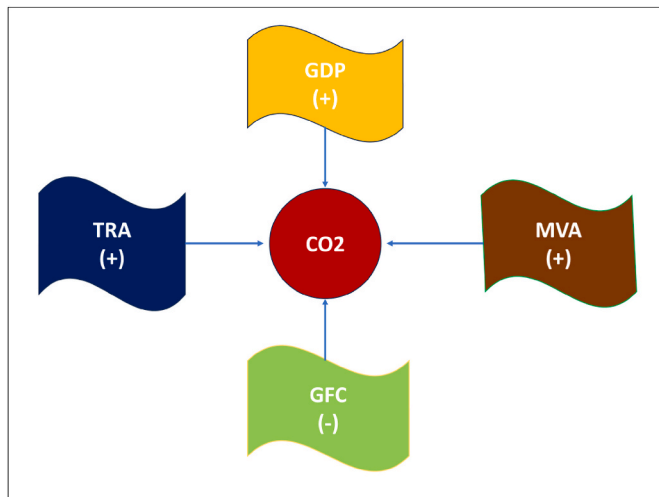
Table 8

Diagnostic tests.

Diagnostic tests	Test Stat.	p-values	Conclusion
Breusch-Godfrey (autocorrelation)	2.572	0.191	No higher-order autocorrelation
ARCH-LM (heteroscedasticity)	0.324	0.726	No heteroscedasticity
Jarque-Bera (normality)	1.684	0.43	Normality
Cusum test	Stable	Stable	Evidence of stability
Cusum of squares test	Stable	Stable	Evidence of stability



Graph 1. Regression lines between variables.



Graph 2. Cusum and Cusum of squares.

0.81 %, while a 1 % increase in $\ln\text{GFC}$ boosts $\ln\text{CO}_2$ by 0.11 %. The results of the KRLS estimation indicate that ceteris paribus, a 1 % increase in average $\ln\text{GDP}$ has a marginal effect on $\ln\text{CO}_2$ of 0.33 %. A 1 % increase in average $\ln\text{TRA}$ has a marginal effect on $\ln\text{CO}_2$ of 0.31 %. In this context, Fig. 1 presents the marginal effects of the independent variables.

Table 10 presents the results of the FMOLS, DOLS, and CCR estimators. The FMOLS results show that ceteris paribus, a 1 % increase in $\ln\text{GDP}$ rises LNCO_2 by about 0.72 %, a 1 % increase in $\ln\text{GFC}$ reduces LNCO_2 by about 0.46 %, and a 1 % increase in $\ln\text{MVA}$ boosts LNCO_2 by 0.30 %. It is shown that a 1 % increase in $\ln\text{TRA}$ increases LNCO_2 by 0.30 %, and a 1 % increase in $\ln\text{TRA}$ raises LNCO_2 by 0.74 %. DOLS results show that a 1 % increase in $\ln\text{GDP}$ raises LNCO_2 by

Table 9

Results of dynamic stimulated autoregressive distributed lag and Kernel-based regularized least squares.

Panel A. Dynamic stimulated autoregressive distributed lag						
$\Delta\ln\text{CO}_2$	Coef.	Std. Err.	t	P > t	[95 % Conf. Interval]	
$\ln\text{CO}_2$	0.136***	0.040	3.420	0.003	0.053	0.220
$\ln\text{GDP}$	0.487**	0.192	2.530	0.020	0.084	0.889
$\Delta\ln\text{TRA}$	0.811***	0.038	21.190	0.000	0.731	0.892
$\Delta\ln\text{GFC}$	0.117**	0.055	2.110	0.048	0.001	0.232
$\ln\text{MVA}$	-0.145***	0.036	-4.020	0.001	-0.220	-0.070
$\ln\text{TRA}$	-0.044	0.030	-1.470	0.158	-0.106	0.019
$\ln\text{GFC}$	-0.122	0.076	-1.610	0.124	-0.281	0.037
Constant	-5.019	2.912	-1.720	0.101	-11.114	1.075
Panel B. Kernel-based regularized least squares (KRLS)						
$\ln\text{CO}_2$	Avg.	t	P > t	P25	P50	P75
$\ln\text{GDP}$	0.337***	4.029	0.000	0.327	0.408	0.511
$\ln\text{MVA}$	0.048	1.331	0.194	-0.048	0.031	0.142
$\ln\text{TRA}$	0.311***	13.006	0.000	0.175	0.289	0.416
$\ln\text{GFC}$	-0.018	-0.455	0.653	-0.060	-0.024	0.050

approximately 1.07 %, a 1 % increase in $\ln\text{GFC}$ reduces LNCO_2 by approximately 0.60 %, and a 1 % increase in $\ln\text{MVA}$ raises LNCO_2 by approximately 1.07 %. In addition, the results of DOLS indicate that ceteris paribus, a 1 % increase in $\ln\text{MVA}$ boosts LNCO_2 by about 0.39 %, while a 1 % increase in $\ln\text{TRA}$ rises in LNCO_2 by about 0.67 %. Finally, the CCR estimation results show that a 1 % increase in $\ln\text{GDP}$ boosts LNCO_2 by about 0.78 %, a 1 % increase in $\ln\text{GFC}$ lowers LNCO_2 by about 0.48 %, and a 1 % increase in $\ln\text{MVA}$ boosts LNCO_2 by about 0.78 %. A 1 % increase in $\ln\text{TRA}$ boosts LNCO_2 by about 0.74 %.

In the final stage of our analysis, we used the symmetric causality test developed by Hacker and Hatemi-J (2006). Therefore, Table 11 presents the results of the symmetric causality test. The distinguishing feature of this test is that it is a bootstrap-based causality test that does not consider the level of stationarity of the series. The test results reject the

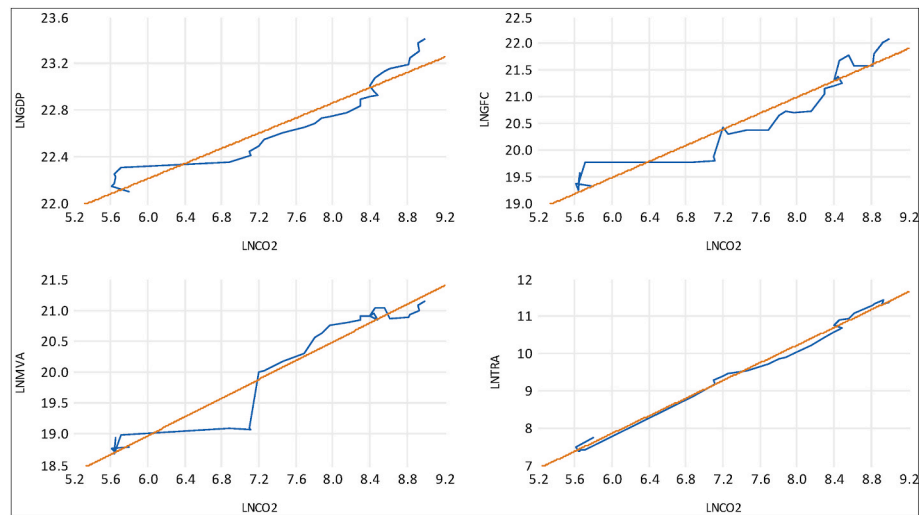


Fig. 1. Representation of Pointwise marginal effect of independent variables on CO2.

Table 10

Robustness tests.

Variable	FMOLS			DOLS			CCR		
	Coefficient	t-Stat.	Prob.	Coefficient	t-Stat.	Prob.	Coefficient	t-Stat.	Prob.
LNGDP	0.72**	2.73	0.01	1.07**	2.42	0.03	0.78**	2.43	0.02
LNGFC	−0.46***	−3.68	0.00	−0.60*	−2.09	0.06	−0.48***	−3.11	0.00
LNMVA	0.30***	5.96	0.00	0.39***	5.20	0.00	0.30***	6.25	0.00
LNTRA	0.74***	19.52	0.00	0.67***	5.48	0.00	0.74***	19.22	0.00
C	−12.57***	−3.10	0.00	−18.70**	−3.03	0.01	−13.37**	−2.84	0.01

Notes. *, **, and *** denote the significance level at the 10 %, 5 %, and 1 %, respectively.

Table 11

The results of [Hacker and Hatemi-J \(2006\)](#) symmetric causality test.

Null hypothesis	Wstat	Critical Values		
		1 %	5 %	10 %
LNGDP $\nrightarrow$ LNCO2	0.265	7.731	4.308	2.997
LNCO2 $\nrightarrow$ LNGDP	0.467	7.327	4.197	2.88
LNGFC $\nrightarrow$ LNCO2	8.857	20.178	12.298	9.505
LNCO2 $\nrightarrow$ LNGFC	9.443*	18.952	11.72	9.157
LNMVA $\nrightarrow$ LNCO2	83.72***	33.43	16.921	12.032
LNCO2 $\nrightarrow$ LNMVA	4.918	19.371	12.208	9.146
LNTRA $\nrightarrow$ LNCO2	1.336	15.404	4.902	2.794
LNCO2 $\nrightarrow$ LNTRA	1.324	14.648	4.459	2.797

Notes. The bootstrap simulation was performed with 10,000 repetitions. *, and *** denote the significance level at the 10 %, and 1 %, respectively.

null hypothesis that LNCO2 is not causal for LNGFC and that LNMVA is not causal for LNCO2. We found a unidirectional causal relationship between LNCO2 and LNGFC and a unidirectional causal relationship from LNMVA to LNCO2. Fig. 2 displays the schematic view of the analysis results. As the evidence shows, there is no causality between GDP and CO2 emissions, meaning that economic growth per se does not drive emissions directly. This shows the importance of the specific emission and environmental outcomes due to the macro- and sector-specific policies. A unidirectional causality from manufacturing value added (MVA) to CO2 emissions showed that industrial growth is indeed an essential source of pollution, indicating that cleaner production technologies are needed. In addition, the bidirectional links between CO2 emissions and gross fixed capital formation (GFC) suggest that although investment in infrastructure influences emissions, increasing these emissions can positively affect investments in sustainable solutions. However, transport energy consumption does not directly affect emissions, meaning that factors like improved energy

efficiency or cleaner transport technologies might mitigate its effects. As such, this calls for legislation promoting rather green industrialization, sustainable infrastructure investment, and efficient transport systems to attain the environmental and economic balance.

5. Discussion of results

Firstly, economic growth is positively related to carbon emissions in Benin, which is statistically significant. The positive relationship between economic growth and carbon emissions in Benin indicates that the current growth trajectory is largely dependent on carbon-intensive sectors. This association suggests that without targeted decarbonization policies, further expansion of economic activities may lead to increased environmental degradation. This result aligns with the early stage of the Environmental Kuznets Curve (EKC), where emissions rise with income due to industrialization and energy use patterns. To mitigate this trend, the integration of green growth strategies is essential. [Grossman and Krueger \(1995\)](#) assert that economic growth hurts the environment until individuals become aware of this issue and adopt new measures. According to the environmental Kuznets curve hypothesis, a positive relationship exists between energy consumption and income, followed by a decline once income reaches a certain threshold. Key measures to mitigate these observations include adopting green fiscal instruments such as carbon pricing in Benin, introducing clean production incentives, and redirecting public investment towards renewable energy infrastructure. Furthermore, enhancing energy efficiency standards across sectors and mainstreaming climate considerations into national economic planning could decouple growth from emissions and support the country's commitments to international environmental goals, such as the Paris Agreement.

Also, gross fixed Capital formation is negatively related to Carbon emissions in the long run but positively related to Emissions in the Short

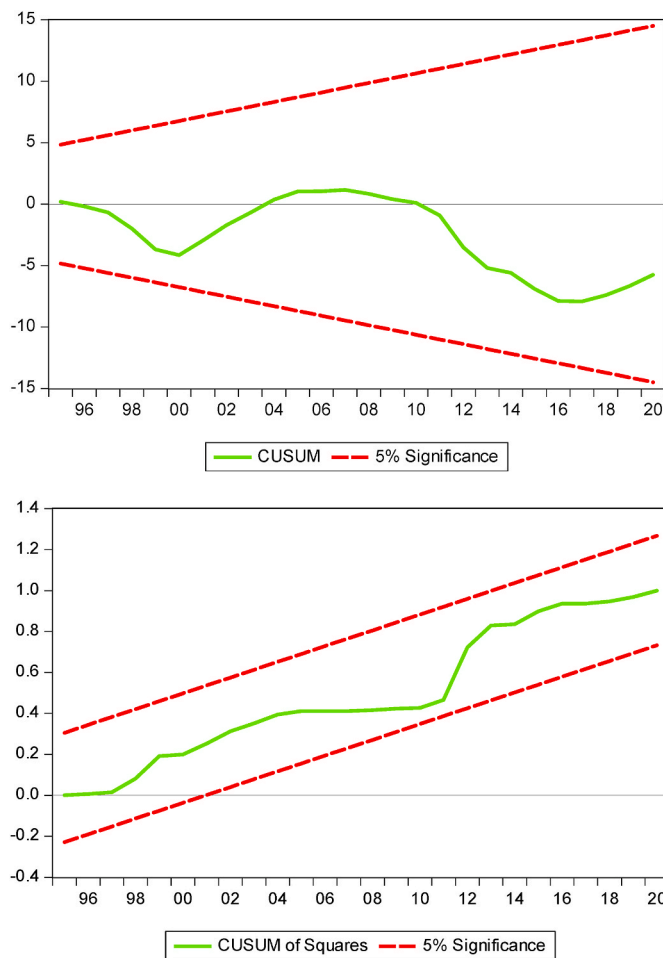


Fig. 2. Schematic view of analysis results.

Run. This negative long-run relationship to emissions suggests that such physical investments in assets and infrastructure may reduce emissions over time, possibly due to efficiency increases or cleaner technologies being adopted. However, the positive relationship in the short run suggests that the initial investment periods in infrastructure or equipment might result in increased emissions before such benefits are realized, somewhat different from an indirect observation in a study conducted by Ouerghi and Tej (2021), who pointed to the possibility that long-term capital might reduce emissions, underlining the role of green investments and environmentally sustainable infrastructure projects. Consequently, manufacturing value added is positively related to carbon emission in Benin in the Long Run and Short Run, and it is Statistically Significant. The positive correlation in emissions, both in the short and long run, shows that the manufacturing sector always contributes to carbon emissions. Where manufacturing is expanded, there is an increase in emissions, as the sector is carbon-emitting. This, therefore, requires clean production technologies, improvement in energy efficiency, and probably regulatory measures that could reduce emissions within the sector. The study by Cadot et al. (2015) examined the relationship between manufacturing value added and energy consumption in transportation, underscoring the pivotal role of manufacturing activities in national energy dynamics. In the context of Benin, the positive association between manufacturing expansion and CO₂ emissions highlights the need to reorient industrial growth through sustainable practices. Policy instruments suitable for this purpose include tax incentives for manufacturers adopting energy-efficient technologies, subsidies for clean energy inputs such as solar-powered machinery, and the creation of eco-industrial zones designed to

minimize environmental externalities. International examples, such as Germany's "Industrie 4.0" and China's "Green Manufacturing Initiative," illustrate the effectiveness of strategic industrial transformation toward low-emission production. Adapting such models to the Beninese context could support a transition to cleaner manufacturing, reduce sectoral emissions, and promote long-term environmental sustainability.

Finally, total final energy consumption by the transport sector is positively related to emissions and is statistically significant in the long and short runs, similar to the study of Balogan (2021), who undertook a comprehensive assessment of the impact of various factors, such as energy consumption in the transportation sector. The finding that energy consumption significantly increases CO₂ emissions underscores the unsustainable nature of Benin's current transport fuel mix, dominated by fossil fuels. This result aligns with sustainability indicators such as SDG 13 (Climate Action), emphasizing the need for a clean energy transition in urban transport systems. Additionally, the positive relationship between industrial output and emissions reflects inefficient manufacturing-transport linkages, suggesting the need for environmentally regulated logistics chains. While this relationship is widely recognized in the global literature, its quantification in the national context offers valuable insights for targeted mitigation. The elasticity estimates derived in this study provide a measurable basis for evaluating the intensity of transport-related emissions relative to economic and energy activity. Countries like Rwanda and India have introduced fiscal incentives for electric motorcycles and rickshaws, reducing urban emissions substantially. In Benin, such incentives could be adapted to tuk-tuks and informal taxis, alongside subsidized charging infrastructure, given the informal nature of urban transport systems. These findings contribute to the development of transport-specific sustainability indicators, such as CO₂ emissions per passenger-kilometer or per unit of transport energy consumed.

6. Conclusion and policy recommendation

In conclusion, the blueprint for harmonizing eco-friendly transport in Benin represents a forward-thinking and pragmatic strategy to address the pressing challenges of energy consumption and environmental impact, coupled with transport feasibility. The proposed blueprint offers a holistic and inclusive approach to creating resilient, eco-conscious cities by integrating sustainable practices into urban development and transportation infrastructure. The emphasis on mixed-use development, innovative infrastructure, and the creation of pedestrian-friendly spaces within urban planning reflects a commitment to reducing dependency on fossil fuels and promoting community-centric living. The blueprint's focus on enhancing public transportation, cycling infrastructure, and walkability addresses immediate transportation needs and contributes to long-term environmental sustainability.

To reduce CO₂ emissions and improve environmental outcomes in Benin's transport sector, the following measures are recommended: the proposed policies supporting electric vehicles and the gradual phasing out of fossil fuel-powered vehicles demonstrate a commitment to cleaner, more sustainable modes of transportation. The governance framework, emphasizing incentives, regulations, and community engagement, underscores the importance of collaboration between government, businesses, and citizens in achieving these ambitious goals. To strengthen the practical dimension of this blueprint, greater attention must be given to the economic and institutional feasibility of the proposed measures in Benin's context. Recognizing Benin's limited fiscal capacity and administrative resources, the proposed policies must be phased and cost-effective, ensuring that initial investments prioritize high-impact and low-cost interventions. The successful implementation of sustainable transport policies in Benin would require due consideration of both the economic feasibility and environmental impact of proposed measures. In this regard, policy adoption should align with existing institutional frameworks and capacity levels. Strengthening

institutional coordination, particularly between national ministries, municipal authorities, and transport agencies, will be vital to ensuring coherence and reducing implementation bottlenecks.

Given that the realities of budget constraints are actual for Benin, this phased approach for adopting such policy measures, with immediate investments in fuel-efficient public transport, followed by a gradual transition to electric vehicle infrastructure, would be more practicable. To mitigate the environmental impact of the transport sector in Benin, a multi-pronged policy approach is essential. Key measures include incentivizing the adoption of electric vehicles through tax exemptions and developing charging infrastructure in urban areas. Enhancing public transport systems, such as expanding bus rapid transit (BRT) and improving route efficiency, can reduce reliance on private vehicles. Enforcing fuel efficiency and emissions standards for imported vehicles, along with mandatory vehicle inspection programs, will help curb pollution.

Urban planning reforms promoting non-motorized transport, compact development, and protection of green spaces are critical to sustainable mobility. Also, careful monitoring and evaluation will be crucial to adapting strategies based on real-world outcomes and lessons learned. The commitment to data-driven decision-making ensures a dynamic and responsive approach to the evolving challenges of urban development. The blueprint focuses on enhancing public transportation, developing cycling infrastructure, and promoting walkability in eco-friendly transport. Policies supporting electric vehicles, including incentives and charging infrastructure, aim to transition away from fossil fuels. The governance framework stresses the importance of incentives, regulations, and community engagement, ensuring that strategies align with local needs. Monitoring and evaluation mechanisms facilitate data-driven adjustments for ongoing improvement.

Additionally, support for clean manufacturing practices should also be prioritized through tax incentives, technical training, and investment in eco-industrial zones. Integrating renewable energy into transport infrastructure, such as solar-powered charging stations, will further reduce the sector's carbon footprint. Strengthening institutional coordination among transport, energy, and environmental agencies is necessary for effective implementation. Additionally, public awareness campaigns and environmental education programs can foster behavioral change toward low-carbon transport choices. Additionally, efforts to build institutional capacity through technical training, knowledge exchange, and partnerships with international organizations can reinforce the long-term sustainability of the proposed reforms. By implementing this blueprint, Benin can pioneer sustainable urban development, providing valuable insights for regions grappling with similar challenges. This research contributes to the global discourse on the sustainable transport sector, offering actionable strategies for mitigating energy consumption and environmental impact in the face of rapid urban growth. Furthermore, the emphasis on international collaboration and private sector involvement recognizes the need for shared responsibility and resources in achieving sustainable development. By successfully implementing this blueprint, Benin has the potential to serve as a model for other regions facing similar challenges, contributing to the global effort to create environmentally conscious and resilient cities for future generations.

6.1. Limitations of the study and future studies

While this study focuses solely on CO₂ emissions, it does not capture other critical dimensions such as particulate matter (PM_{2.5}), noise pollution, and land use impacts. Future research should adopt a multi-indicator environmental framework using datasets on air quality, ecological footprint, and urban congestion to present a holistic view of transport's environmental impact in Benin. Also, it concludes with specific financial and environmental indicators, which might not represent every detail in the changing dynamics of energy use. Other variables to consider could revolve around technological changes and

policy issues; other research could also consider looking into trends over more extended periods or in regions similar to this one. Future research should expand the analytical scope by incorporating a broader set of environmental indicators. A multi-dimensional evaluation encompassing air quality metrics, noise levels, land resource use, and ecological disruption would offer a more holistic understanding of the transport sector's environmental footprint in Benin and inform more integrated policy responses. This would also help better explain the dynamics influencing the emissions, thus enabling more focused sustainability strategies.

CRedit authorship contribution statement

Salwa Bajja: Methodology, Data curation, Writing – original draft, Formal analysis, Funding acquisition, Conceptualization. **Ali Celik:** Software, Writing – review & editing, Methodology. **Michael Provide Fumey:** Investigation, Writing – review & editing, Formal analysis. **Vodoungnon Anignikin Padonou:** Investigation, Writing – review & editing, Data curation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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