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Energy and sustainable development in cities: A case study of Bogotá

Clara Inés Pardo Martínez

School of Administration, Universidad del Rosario, Bogotá, Colombia

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ABSTRACT

Developing energy solutions that positively impact issues related to economic growth, the environment and social equity in cities is important. A better understanding of urban energy use, particularly in developing countries, can strengthen energy security, climate change mitigation and local pollution abatement. This study seeks to evaluate the trends in energy use and CO_2 emissions in Bogotá by determining energy flows through input and output analyses. The study establishes a relationship between energy and sustainable development by applying correlation analyses. Bogotá consumes 24% of the electricity produced in the country, generates 96010.1 TJ of the gross energy, and emits CO_2, NOx and CO (carbon monoxide). Correlation analyses indicate a strong and direct relationship between energy, economic variables and social variables, with the majority of the correlation coefficients exceeding 0.8. Strong positive correlations are particularly observed between energy consumption, the gross domestic product, the human development index and CO_2 emissions. Energy per capita and CO_2 emissions per capita also strongly correlate with the human development index and GINI coefficients. These results demonstrate that energy increasingly influences the development, economic growth and welfare of the city population. Thus, formulating strategies that will improve energy use in cities is important.

1. Introduction

Currently, half of the world's population resides in cities, which account for two-thirds of the global energy demand. As rapid urban growth continues, particularly in developing countries, energy use in cities and associated levels of GHG (greenhouse gas) emissions are projected to increase unabated. Current projections indicate that approximately 70% of the world's population will live in cities by 2050; these areas will produce 80% of the world's greenhouse gas emissions [1]. Moreover, the International Energy Agency estimates that global city energy use will increase by 1.9% per annum from approximately 7900 Mtoe (million tonnes oil equivalent) in 2006 to 12,374 Mtoe in 2030. More than 70% of global GHG emissions are currently generated in urban centres [2].

Urban decision makers must understand the implications of energy, pollution and sustainable development interactions and the potential influences of future global climate changes. Energy use from the perspective of sustainable development involves the complex interactions of citizens, government and nongovernmental organisations, and businesses. This complexity requires a diagnostic analysis and evaluation of the main trends in energy use and CO_2 emissions to define integrated strategies that involve active management, land use planning, new civil infrastructure, etc. The combined effects of these strategies may be more beneficial than the achievements of any single activity, agency or organisation acting unilaterally [3].

A sustainable approach to energy requires solutions that simultaneously address development issues related to economic growth, environmental protection and social equity. Fig. 1 shows the relationship between energy and urban forms, where energy technologies and distribution systems are the main factors that shape the city, determine a city's needs (the energy demand for spatial structures in support of human activities) and determine the resilience inherent in every settlement [4]. Therefore, the patterns of consumption, production and infrastructure in urban systems can have a positive or negative effect, depending on their design, operation and maintenance.

In recent years, new approaches to energy and sustainable development have been proposed. A study on Chinese cities' energy use, CO_2 emissions and their effects on the urbanisation process has determined that cities account for 40% of China's energy usage and CO_2 emissions and that the per capita energy consumption and CO_2 emissions have increased [5]. In another study, the future of cities has been evaluated by considering policies for mitigating climate change and by considering increasingly problematic energy

E-mail addresses: cipmusa@yahoo.com, clara.pardo@urosario.edu.co.

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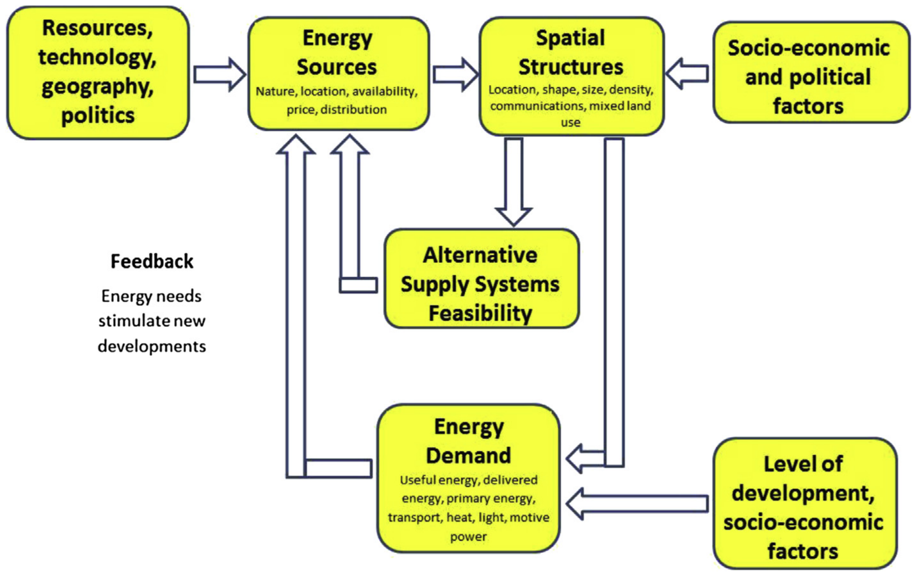

Fig. 1. Energy and urban forms [4].

scenarios; specifically, the importance of the configuration of land, the design and use of buildings that reduce energy needs, and the use of renewable energy sources while adapting to climatic conditions is determined [6]. Moreover, the energy structure and mechanisms underlying energy flows have been analysed in the urban ecological economic system of Xiamen City in China; the process and amount of energy exchange and the quality and level of energy exchange in a city must be thoroughly investigated [7]. The design and application of an integrated energy planning strategy in cities and territories has also been studied. Notably, the development of long-term energy plans for urban regions is complex because the plans must integrate several aspects of development (environmental, social, and technological), various sectors (residential, industrial, and transport), multiple energy sources (gas, oil, and electricity) and diverse technologies that compound the energy system in all stages [8]. A model that includes systematic analyses of energy conversion and utilisation and air pollution mitigation has also been proposed to determine patterns of energy resource allocation and capacity expansion options for energy technologies under various air pollution emission reduction schemes, which could reduce costs while alleviating air pollution [9]. Finally, energy and environmental planning systems for small- and medium-sized cities and the role of municipalities have been evaluated through an optimisation model to show that distributed energy generation alternatives and their inclusion in the municipal energy generation structure and regional energy planning process may be helpful for mayors and municipal counsellors and for establishing energy policies to save energy and reduce carbon dioxide emissions [10].

Other studies have determined the relationship between energy and urban planning and have arrived at several key findings. First, energy requirements differ between urban and rural areas because of expenditure patterns and inequalities in income; urban households generally require more energy than suburban or rural households, indicating the importance of accounting for patterns of energy consumption in the urban planning process [11]. Second, urban forms or physical structures (i.e., households and mobility) determine energy consumption in cities and may cause environmental problems; thus, new planning strategies for future urban structures should consider energy and environmental aspects [12]. Lastly, urban features, such as land use patterns, industrial activities, population, infrastructure and public services, are determinants of energy consumption and CO_2 emissions; therefore, urban development generally involves greater energy consumption and CO_2 emissions [13].

These studies have analysed energy use in cities by accounting for environmental impacts of new policies, energy flows and energy planning strategies. The analyses reveal that effective urban planning strategies require an energy usage model and environmental considerations that account for the different features of cities that determine energy supply and consumption. Although prior studies have established a better understanding of the relationship between energy consumption and sustainable development, the trends in energy and sustainable development (economic, environmental and social issues) in cities of developing countries have not been analysed empirically. Hence, the main goal of this study is to determine the relationships between energy and sustainable development by assessing several indicators for the case study of Bogotá and developing a model for Latin American cities where studies are limited and where the integration of energy considerations with urban planning is insufficient in many cases. These areas experience greater energy consumption and environmental problems.

The following section reviews the energy system in Bogotá. Section 3 describes the methodology employed and the data used throughout the paper. Section 4 provides an overview of the main results related to energy and sustainable development and discussions. Section 5 summarises the conclusions of this study.

2. Energy system in Bogotá, Colombia

Since the 1990s, the Colombian government has transitioned from being the sole player in the energy sector (i.e., the overseer of the resource administration and investors, with near absolute ownership of the electricity sector) to a paradigm with a clear separation of roles between investors and the government. The latter is responsible for policy-making, regulating and exercising control, conducting surveillance, conducting electricity sector planning, performing regulatory functions for transmission expansion activities, and indicating needs for generation expansion activities [14]. Fig. 2 describes the Colombian power sector.

In Bogotá, the energy demand comes from five major sectors (see Fig. 3.): residential, industrial, transportation, services and others (government buildings, street lighting, etc.). These sectors consume an average of 201 PJ of energy per annum [15,16]. Moreover, the key factors that determine energy demand in the city are economic growth, demographics, industry composition, and living standards. On average, in the last decade, the transportation sector was the highest consumer of energy, while the industrial sector had reduced its relative consumption through the implementation of new technologies and fuel substitutes. The transportation and services sectors have increased their relative energy consumption.

Fig. 4 represents Bogotá's primary and secondary energy composition averaged over the last decade by sector. The industrial sector mainly consumed electricity and natural gas; the transport sector consumed petroleum products (gasoline and diesel); the residential sector consumed primarily electricity and natural gas; and the services sector consumed mostly electricity and petroleum products [17,18].

3. Methods and data

In this section, the methods and data used in this study are explained. We have accounted for the availability of data to obtain reliable time series with a level of detail sufficient to establish different relationships between energy and sustainable development. This study consists of three phases. First, we define energy flows and emissions in Bogotá. Second, we formulate indicators and analyse their trends over time in terms of energy and sustainable development. Third, we apply correlation analyses to determine the main relationships between energy and sustainable development.

3.1. Methods to measure energy flows and emissions

Energy is fundamental for all urban activities, and its use determines the level of development. To measure energy flow in

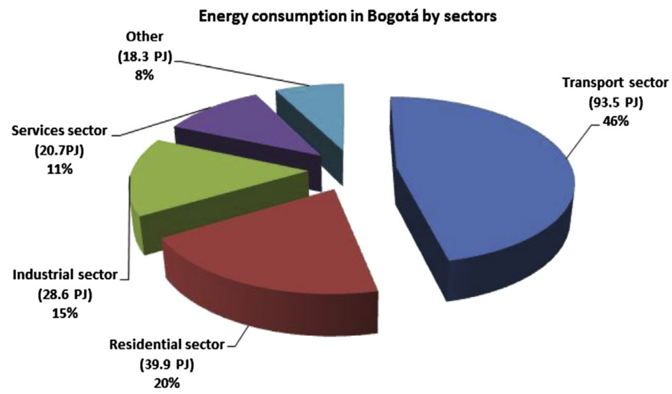

Fig. 3. Energy consumption by economic sector in Bogotá (average of the last decade).

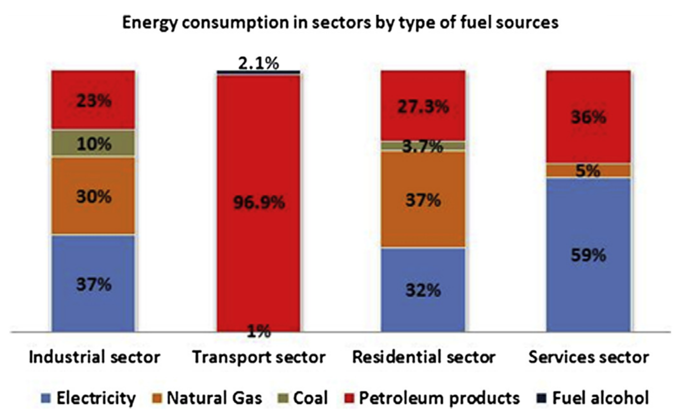

Fig. 4. Bogotá's primary and secondary energy composition averaged over the last decade by sector.

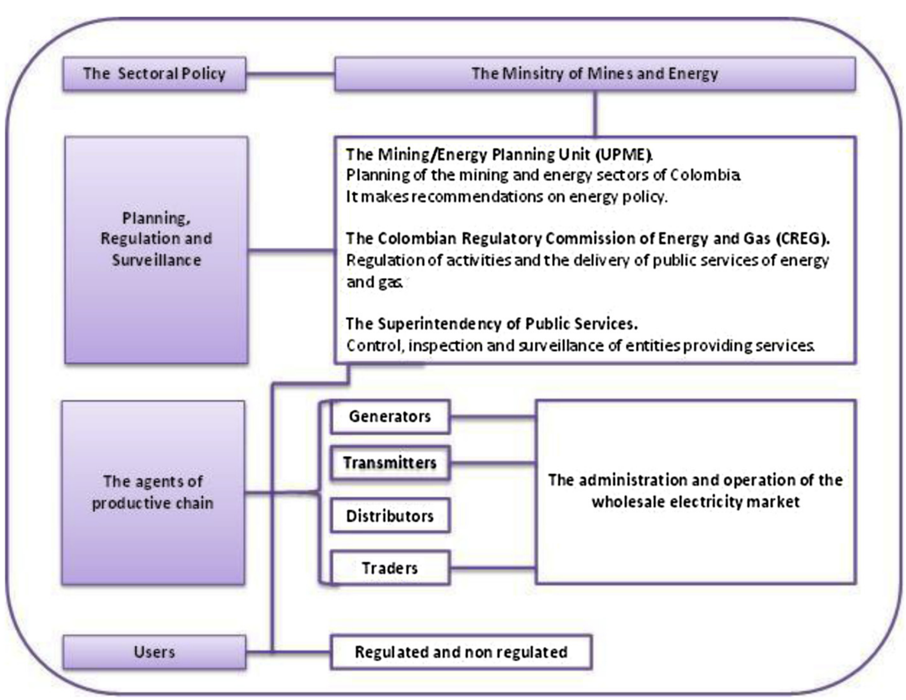

Fig. 2. Colombian power sector [14].

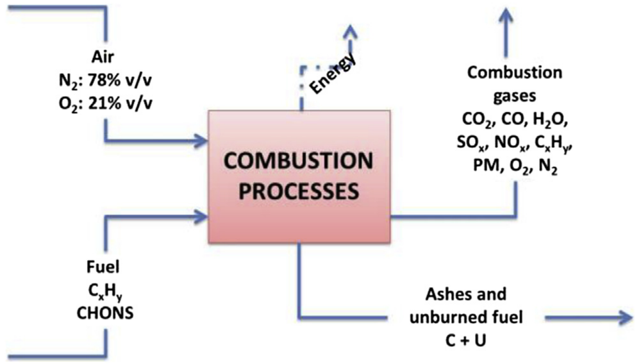

Fig. 5. Combustion processes [22].

Bogotá, the following energy sources are analysed: electricity, gasoline, diesel, coal, natural gas and liquid petroleum gas (LPG). Energy released is also calculated by applying concepts of energy balance.

In the case of emissions, this study assesses CO_2 (carbon dioxide), CO (carbon monoxide), NO_2 (nitrogen dioxide), SO_2 (sulphur dioxide), CxHy (hydrocarbons) and PM (particulate matter) products from combustion processes that utilise energy sources analysed herein. The calculations are conducted according to the following equations by considering the stoichiometry of combustion reactants.

$$
\begin{aligned}
&C + O_2 \xrightarrow{\Delta} CO_2 \\
&C + \frac{1}{2} O_2 \xrightarrow{\Delta} CO \\
&2H + \frac{1}{2} O_2 \xrightarrow{\Delta} H_2O \\
&S + O_2 \xrightarrow{\Delta} SO_2
\end{aligned}
\tag{1}
$$

Fig. 5 illustrates the typical combustion processes (chemical reactions involving the oxidation of fuel by oxygen from air) used to develop the model for estimating emissions. The main assumptions in determining emissions are as follows: i. Material balance is calculated in a steady state (i.e., the variables in the system do not change over time) [19]; ii. The amount of excess air is 20% [20,21]; iii. Coal shows an incomplete combustion rate of 30% due to obsolete technology; iv. 5% of the fuel mass is not completely oxidised, 90% of which is maintained as C_xH_y in the emissions; v. 95% of the sulphur from fuel is oxidised to generate SO_2 without producing particulate matter [22]; vi. 50% of nitrogen from fuel is oxidised to generate NO_2 [22]; vii. 2.5% of nitrogen from air is oxidised to generate NO_2 [22]; and viii. 90% of ashes from fuel generate particulate matter, while the other 10% remain ashes.

3.2. Proposed indicators

To evaluate the relationship between energy and sustainable development in Bogotá, several indicators are needed to determine energy dynamics, urban growth trends, and social and environmental features during the 2000–2011 period. Generally, higher incomes correspond to more energy-intensive lifestyles; thus, urban residents' energy demand per capita is greater than that of rural residents. Hence, urban habitats must achieve more efficient and cleaner settlements and better standards of living. Therefore, sustainable city development requires an effective infrastructure that contributes to economic growth and improves the quality of life, i.e., efficient buildings, a reliable power grid and capable mobility solutions [5]. The indicators (Table 1) are based on the reliability and availability of detailed data for Bogotá in the last decade. In the city, final energy and electricity consumption, divided among the industrial and residential sectors, are good variables to describe energy trends in the city; gross domestic product (GDP) and the number of industries indicate urban economic growth and may also reflect energy consumption [23]. Emissions characteristics reflect the quality of the underlying energy sources. Indicators related to CO_2 emissions reflect the environmental conditions in cities. Finally, social indicators, such as GINI, the human development index (HDI) and urban density, can be used to generate trends in energy consumption and improvements to the welfare of the city population based on the features of the energy supply [24].

3.3. Correlation analysis

To understand the relationship between energy and sustainable development based on the indicators, a correlation analysis is applied wherein the product–moment correlation coefficient, ρ, is

$$
\hat{\rho} = \frac{\sum_{i=1}^{n} w_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt[2]{\sum_{i=1}^{n} w_i (x_i - \bar{x})^2}\sqrt[2]{\sum_{i=1}^{n} w_i (y_i - \bar{y})^2}} \tag{2}
$$

where w_i is the weight, if specified, or $w_i = 1$ if the weight is not specified. $\bar{x} = (\sum w_i x_i)/(\sum w_i)$ is the mean of x, and $\bar{y}$ is similarly defined [25,26]. The significance level can be calculated using the property of the statistic t = rSQR[(n − 2)/(1 − r^2)] which is distributed approximately as Student's t distribution with n − 2 degrees of freedom. Computations have been carried out using the relevant Stata command.

Table 1
Indicators used in Bogotá.

Indicators		
Factor	Variable	Intensity – measurement
Energy	Final energy consumption (TJ) Electricity consumption in industrial and residential sectors (kwh)	Final energy consumption per capita (GJ per person) Electricity consumption in the residential sector per capita (kwh per person)
Economic issue	GDP (million US$2005) Population Number of industries (an industrial establishment has a minimum of 10 employees and an annual minimum production value of US$50,000)	Energy intensity: final energy consumption per GDP (TJ/million US$2005) Electricity consumption in the industrial sector per industry (kwh per industry)
Environmental issue	Emissions: sulphur dioxide SO_2 (ppb), particulate matter (μg/m^3), CO_2 emissions (kilotonnes)	Energy consumption per CO_2 emissions (TJ/kilotonnes) CO_2 emissions per capita (tonnes/person) CO_2 emissions per GDP (tonnes/million US$2005)
Social issue	GINI, HDI, urban density (population/km^2)	

In this study, two correlation coefficients are applied: Pearson's (to calculate the linear correlation between two variables) [26] and Kendall's (to determine the differences between the probabilities of the one factor increasing or decreasing with respect to another factor) correlations [28]. Pearson's correlation is a parametric measure that is dependent on the distribution of data to measure the linear association of two variables, whereas the Kendall correlation is a non-parametric measure used to determine the monotone dependence of two variables. Both methods produce coefficients ranging from −1 to 1. If the correlation coefficient approaches zero, then a weak correlation exists between the two variables. If the correlation coefficient is close to 1 or −1, then a strong correlation exists between the two variables. The use of these two methods allows for more complete information to be obtained on the relationship between energy and sustainable development in Bogotá.

3.4. Data

The main data sources were the databases and reports produced by the Departamento Nacional de Estadística (Colombian Department of Statistics, DANE), the Departamento Nacional de Planeación (National Department of Planning, DNP), the Unidad de Planeación Minero Energética (Unit of Mines and Energy Planning, UPME), and the Secretaría Distrital de Planeación (District Planning Secretary of Bogotá).

4. Results and discussion

This section describes the main results of the analyses, which explore the relationship between energy and sustainable development in Bogotá by using the methods proposed in Section 3.

4.1. Energy flow and emissions analyses for Bogotá

Throughout its history, Bogotá has experienced energy transitions when an energy source (or groups of sources) that dominates the energy market in a particular period is eventually replaced with better energy sources [29]. In Bogotá, energy transitions have been driven by economic growth, technological change and environmental changes as well as social policies and regulations.

Energy flows in Bogotá (see Fig. 6.) include electricity (mostly for personal use) and fossil fuels (which define the productive and economic system in the city). Electricity is mainly generated from two hydroelectric plants (Guavio and Chivor). In 2010, Bogotá consumed 24% of the total electricity of the country (36849.6 TJ). The city also consumed 20257.1 TJ of the coal, 31018.6 TJ of the gasoline, 27853.5 TJ of the diesel, 16775.4 TJ of the natural gas, and 2110.1 TJ LPG, while the energy released totalled 132726.1 TJ [30,31].

Combustion processes generate varying emissions, depending on the energy source, technology, operating conditions and environmental control systems. In Bogotá, considering a gross energy generation of 96010.1 TJ by the combustion of gasoline, diesel, coal, natural gas and LPG (2349 kt), the emissions generated in 2010 were 4705 kt of CO_2, 2125 kt of NO_2, 1286 kt of CO, 113 kt of CxHy, 19 kt of PM, and 34 kt of SO_2 (Fig. 7.). These emissions, which deteriorate the air quality over the city, have been mainly generated by mobile and fixed sources in recent decades [32].

Emissions in the urban context are important because they are linked directly to climate change, particularly in the case of greenhouse gas emissions, which are directly linked to energy use [33], as demonstrated in the results of the energy flow and emissions analysis. Table 2 shows how various land use changes can affect the urban energy demand and greenhouse gas emissions. Thus, urban forms are important for encouraging sustainable urban development. Moreover, Table 2 shows that denser areas improve the viability of public transport, generate fewer material requirements for new industry facilities and buildings, and promote reduced energy consumption, among other benefits that result from the integration of energy aspects into the planning and management of cities. These issues must be considered in the process of urban planning, particularly in the case of Bogotá.

4.2. Indicators proposed to analyse the relationship between urban energy and sustainable development

4.2.1. Energy and economic indicators

Energy consumption in Bogotá has increased in the last three decades. Similarly, the GDP has increased as the energy sector GDP over the last decade averaged 2.63%. Fig. 8 shows the trends in energy consumption and GDP over the last decade in Bogotá.

In the last decade, energy consumption has increased by approximately 40%, whereas the GDP has increased by more than 50%, with average annual growth rates of 3% and 4%, respectively. These results indicate that energy is a key for economic growth. Moreover, these results concur with previous studies [34] that have

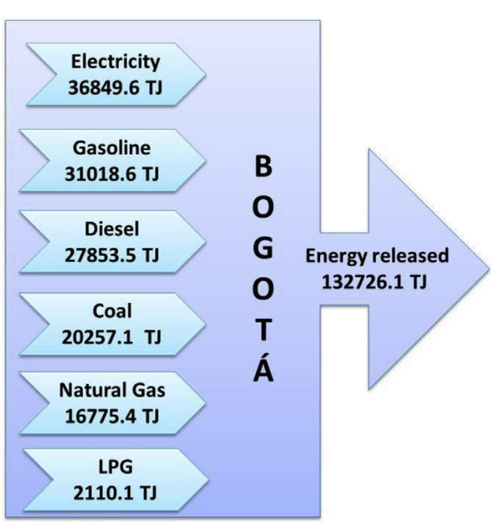

Fig. 6. Energy flow analysis for Bogotá, 2010.

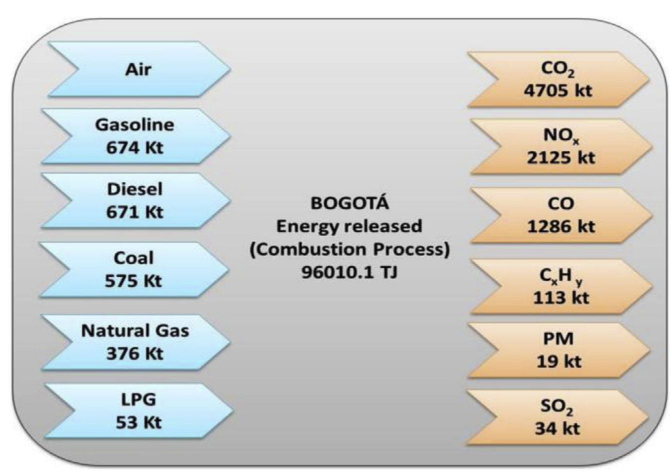

Fig. 7. Relationship between energy sources and emissions in Bogotá, 2010.

Table 2
The relationship between land use and energy demand in cities.

Land use	Mechanism	Energy impacts
Combination of land use factors (shape, size, interspersion, etc.)	Travel requirements (distance & frequency)	Variation up to 150%
Interspersion of activities	Travel requirements (distance or trip length)	Variation up to 130%
Shape of urban area	Travel requirements	Variation of up to 20%
Density/clustering of transportation routes	Facilitates public transport use	Energy savings up to 20%
Density/mixing of land uses/built structures	Facilitates cogeneration of heat and power (CHP)	Energy savings of 15%
Layout/orientation/design	Passive cooling/heating with solar energy	Energy savings up to 20%
Siting/layout/landscaping/ materials	Microclimate optimisation	Energy savings of at least 5%

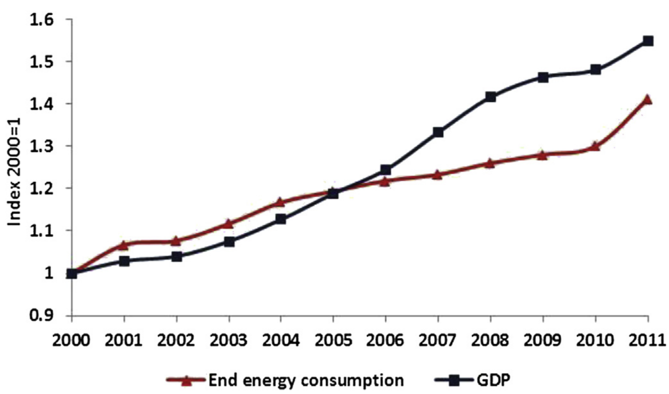

Fig. 8. Trends in energy consumption and GDP in Bogotá (2000–2011).

demonstrated the long-term and short-term causal effects of energy consumption on GDP in developing countries.

In Bogotá, energy intensity, measured as TJ/million US$2005, averaged 5.12, whereas the energy per capita averaged 28.41 GJ/person in the last decade. The per capita energy consumption value is below the global average (75 GJ per capita), mainly because the local consumption patterns and climatic conditions do not require space heating [35]. However, the electricity trend shows that, annually, a person consumes 545.1 kWh, whereas an industry consumes approximately 596 MWh. Fig. 9 shows the trend of the intensity indicators for energy and electricity in Bogotá.

4.2.2. Energy and environmental indicators

Cities play a central role in reducing greenhouse gas emissions and mitigating climate change through local action plans and policies via technical, institutional, policy and financial measures [36].

In Bogotá, emissions have exhibited a different trend (see Fig. 10). SO_2 decreased from 12.80 ppb in 2000 to 3.5 ppb in 2011, and particulate matter decreased from 65 μg/m^3 in 2000 to 51.6 μg/m^3 in 2011 due to improvements in the quality of gasoline and diesel fuels and the implementation of new legal requirements based on European specifications. In the case of gasoline, fuel alcohol was added to the mixture in 2005, the number of aromatics was reduced in 2009 (from 28% to 20% in regular gasoline and from 35% to 22% in premium gasoline), and the sulphur content was reduced (to 200 ppm) in 2010. For diesel, the sulphur content was reduced to 500 ppm, and biodiesel was added in 2010 [37,38]. These air quality improvements offer social benefits, such as improved health, longevity and quality of life for the local population [39,40].

However, CO_2 emissions in Bogotá have increased from 3633 kt to 4759 kt over the last decade (Fig. 10). This trend is directly related to the traditional energy model in which a city meets its energy requirements through burning fossil fuels [41].

However, intensity indicators have shown that in the last decade, on average, 33.04 TJ of consumed energy generated one kt CO_2, or 1.37 tonnes of CO_2 per capita and 155.67 tonnes of CO_2 per one million US$. These indicators are lower than the global average (4.29 tonnes of CO_2 per capita) due to the nature of the local energy matrix in which a substantial portion of the electricity produced is from hydroelectric plants; this reinforces the importance of energy source and energy consumption patterns on environmental effects [42,43].

4.2.3. Energy and social indicators

Bogotá faces challenges related to societal problems, such as high levels of poverty and an increasing number of people whose basic needs are not satisfied. The National Energy Plan 2006–2025 suggests that through economic growth, including a solid energy sector, an equalitarian and unified society with less poverty and more opportunities may be achieved [44].

Fig. 11 shows the trends in the energy consumption, GINI, HDI, and urban density. Energy consumption, the HDI and urban density have increased in the last decade, whereas the GINI coefficient has decreased, demonstrating the importance of energy in improving social conditions and development due to its linkage with economic productivity, health, nutrition, education and environmental

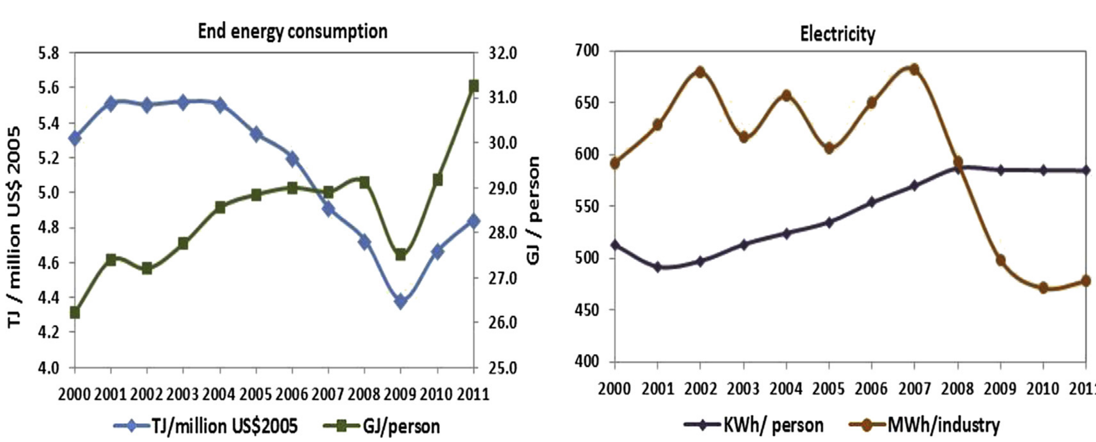

Fig. 9. Intensity indicators – electricity and energy in Bogotá (2000–2011).

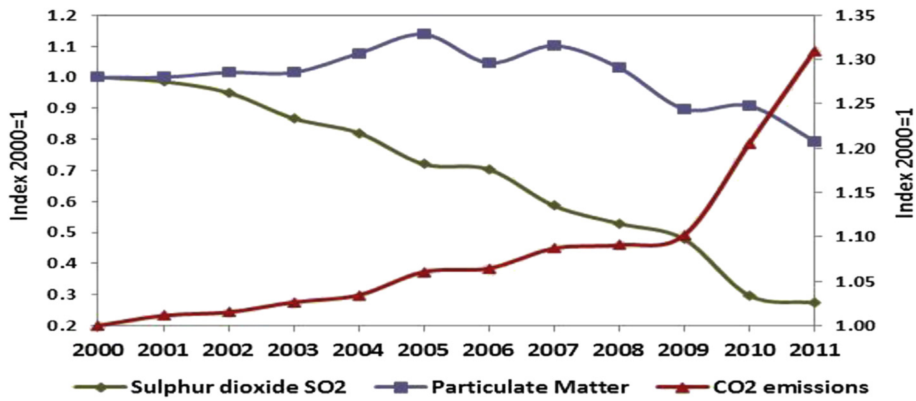

Fig. 10. Trends in emissions in Bogotá (2000–2011).

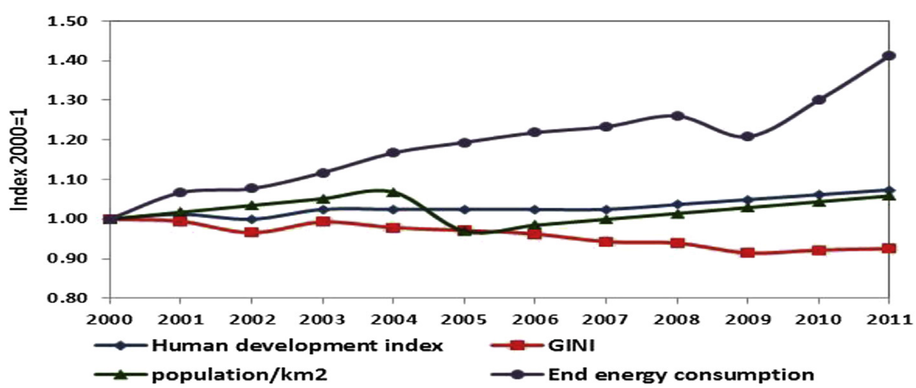

Fig. 11. Trends in energy and social indicators in Bogotá (2000–2011).

quality. In contrast, low levels of modern energy services tend to drive poverty rates higher and undermine development [45].

4.3. Correlation analyses

To understand the relationship between energy and sustainable development in Bogotá, correlation analyses were applied with the main indicators as explained above. The results of the correlation analyses show strong relationships between the following: energy, economic growth and development; energy and environmental effects; and energy and social conditions. Indeed, unsustainable, inefficient and unclean energy consumptions are widely reflective of poverty in most developing countries; thus, policy-makers and international organisations have concluded that the provision of modern energy services represents a major avenue towards decreasing poverty and increasing development [46].

Table 3 shows the correlation analysis for Bogotá using variables related to economic, environmental and social issues. The relationships among energy, population, number of industries, GDP, CO_2 emissions and HDI indicate that these variables are positively related, suggesting that a higher energy consumption correlates with a greater number of industries, higher GDP, greater CO_2

Table 3
The correlation analysis for Bogotá using variables that reflect economic, environmental and social issues (2000–2011).

	Energy consumption	Number of industries	GDP	CO_2	HDI	GINI
Pearson's correlation						
Energy consumption	1					
Number of industries	0.855* (0.000)	1				
GDP	0.920* (0.000)	0.953* (0.000)	1			
CO_2	0.914* (0.000)	0.884* (0.000)	0.877* (0.000)	1		
HDI	0.911* (0.000)	0.948* (0.000)	0.917* (0.000)	0.932* (0.000)	1	
GINI	−0.813* (0.001)	−0.860* (0.000)	−0.928* (0.000)	−0.794* (0.002)	−0.777* (0.002)	1
Kendall's correlation						
Energy consumption	1					
Number of industries	0.727* (0.001)	1				
GDP	0.909* (0.000)	0.818* (0.000)	1			
CO_2	0.909* (0.000)	0.812* (0.000)	0.977* (0.000)	1		
HDI	0.712* (0.001)	0.853* (0.000)	0.879* (0.000)	0.849* (0.000)	1	
GINI	−0.719* (0.002)	−0.645* (0.003)	−0.812* (0.000)	−0.832* (0.000)	−0.668* (0.000)	1

*: Significant at the $p \leq 0.05$ level.
Figures in parentheses indicate the significance level.

Table 4
Correlation analysis for Bogotá using energy intensity indicators and sustainable development in the productive sector (2000–2011).

	Final energy consumption per GDP (TJ/million US$2005)	Electricity consumption (kWh per industry)	CO_2 emissions per GDP (TJ/million US$2005)
Pearson's correlation			
Final energy consumption per GDP (TJ/million US$2005)	1		
Electricity consumption (kWh per industry)	0.6976* (0.011)	1	
CO_2 emissions per GDP (TJ/million US$2005)	0.9196* (0.000)	0.602* (0.038)	1
Kendall's correlation			
Final energy consumption per GDP (TJ/million US$2005)	1		
Electricity consumption (kWh per industry)	0.500* (0.005)	1	
CO_2 emissions per GDP (TJ/million US$2005)	0.809* (0.000)	0.551* (0.001)	1

*: Significant at the $p \leq 0.05$ level.
Figures in parentheses indicate the significance level.

Table 5
Correlation analysis for Bogotá using energy intensity and social indicators (2000–2011).

	Energy per capita (GJ per person)	Electricity consumption per capita (kWh per person)	CO_2 emissions per capita (tonnes/person)	HDI	GINI
Pearson's correlation					
Energy per capita (GJ per person)	1				
Electricity consumption per capita (kWh per person)	0.665* (0.018)	1			
CO_2 emissions per capita (tonnes/person)	−0.998* (0.000)	−0.650* (0.021)	1		
HDI	0.779* (0.002)	0.826* (0.000)	−0.761* (0.004)	1	
GINI	−0.604* (0.037)	−0.884* (0.000)	0.585* (0.045)	−0.777* (0.002)	1
Kendall's correlation					
Energy per capita (GJ per person)	1				
Electricity consumption per capita (kWh per person)	0.595* (0.011)	1			
CO_2 emissions per capita (tonnes/person)	−0.992* (0.000)	−0.585* (0.001)	1		
HDI	0.713* (0.002)	0.669* (0.006)	−0.702* (0.002)	1	
GINI	−0.575* (0.016)	−0.748* (0.003)	0.564* (0.016)	−0.680* (0.005)	1

*: Significant at the $p \leq 0.05$ level.
Figures in parentheses indicate the significance level.

emissions and improved HDI values. Furthermore, the relationship between energy and GINI shows that an increase in energy consumption correlates with a decrease in inequality. These results imply a possible causal relationship between economic growth and sustainable development. However, whether energy consumption determines the GDP is unknown; if so, then the economy is energy dependent, and energy is fundamental to achieve economic growth [47]. In contrast, if energy consumption determines GDP, then the economy is not energy dependent but rather requires energy policies that promote growth and sustainable development [48].

Regarding the relationship between energy intensity indicators and sustainable development in the productive sector, the correlation analysis reveals a positive association between energy intensity (measured as energy per GDP), electricity consumption per industry, and tonnes of CO_2 per GDP (see Table 4). Therefore, strengthening measures and programs to improve energy efficiency is important, particularly within the productive sectors of the city. In the case of Bogotá, the Ministry of Mines and Energy has developed a program for the rational and efficient use of energy (PROURE) with the aim of reducing energy intensity and promoting renewable energy; the program seeks to optimise electricity energy use through promoting more efficient boilers and illumination, applying energy management systems, and adopting cogeneration, among other activities [49].

The results of the correlation analyses between energy intensity and social indicators (see Table 5) indicate that higher energy consumption per capita drives higher electricity consumption per person, greater HDI values, and improved equality. CO_2 emissions per capita are negatively correlated with energy intensity, indicating that improvements in energy use, a better quality of life, and equality are associated with better environmental performance. These results reinforce the importance of achieving economic growth for decreasing inequality and promoting sustainable energy consumption. Therefore, carbon emissions, energy consumption and GDP per capita are interchangeable measures of inequality because these indicators reflect the standards of living in cities [50]. In the case of Bogotá, these results reflect technological progress and fuel quality improvement, for which the main strategies are the replacement of incandescent lamps, the promotion of higher energy efficiency in appliances, and the design and construction of sustainable buildings [51]. Moreover, these results concur with prior studies, which establish that more equal societies have smaller ecological footprints and better welfare and that with existing technology and new innovation, wealthier countries can substantially reduce their carbon emissions without reducing the life expectancy [52,53].

The correlation values for the selected variables and indicators are mostly greater than 0.8 ($R > 0.8$). An R value close to 1.0 indicates a strong relationship between the two variables. The results confirm that energy and sustainable development in cities are fundamental to improve welfare and development. Moreover, the results of both Pearson's and Kendall's correlations are consistent (see Tables 3–5), indicating that the results from this study are robust. Urban sustainability goals are related to the maximisation of positive factors from the interaction of three sustainable elements (e.g., a high-quality labour market, increasing returns on energy use, and economies of density in pollution control) and the minimisation of negative factors (e.g., traffic congestion and air, water and soil pollution). Therefore, sustainable cities are characterised by not only a clean environment but also a thriving socio-economy and environment [54].

Finally, this analysis is important for developing adequate urban planning that integrates the energy sector, which is a key factor for achieving sustainable development and better welfare, particularly

Table 6
Energy aspects in land use planning [55].

Land use planning activities		Energy considerations		Outputs
Land use problem analysis				Energy-integrated land use planning
Land use goal, objectives and criteria formulation	+	Existing energy goal, objectives and criteria	=	
Land use surveys and database development and analysis	+	Energy survey data (supply, consumption, demand)	=	
Alternative growth scenarios and solution formulation	+	Energy demand and supply scenarios	=	
Alternative growth scenarios and solution analysis	+	Energy implications of growth scenarios and proposed solutions	=	
Land use policy formulation (based on analysis)	+	Existing energy policies and plans/programs	=	
Land use policy impact analysis	+	Energy-environment link assessment results	=	
Land use policy support activities formulation	+	Energy plan project implementation and results	=	
Land use management and plan implementation strategy development	+		=	
Land use plan implementation				
Land use monitoring and management	+	Energy consumption monitoring and management	=	Energy-integrated land use plan management

Table 7
Energy aspects in urban development planning [55].

Urban planning activities		Energy considerations		Outputs
Analysis of urban development concerns	+	Energy issues (supply, consumption, demand) analysis	=	Energy-integrated urban development planning
Urban development goal, objectives and criteria formulation	+	Existing energy goal, objectives and criteria	=	
Urban development surveys and analysis of sectoral plans and profiles	+	Energy survey data (supply, consumption, demand) and database	=	
Alternative growth scenarios and solution formulation	+	Energy demand and supply scenarios	=	
Alternative growth scenarios and solution analysis	+	Energy implications of growth scenarios and proposed solutions	=	
Urban development policy formulation and sectoral policies and regulations	+	Formulated and enforced energy policies and plans/programs	=	
Urban development and sectoral policy impact analysis	+	Energy-environment impact assessment	=	
Urban development and sectoral policy support activities formulation	+	Energy plan project implementation and results	=	
Urban plans and program implementation and management strategies	+	Energy management plan and energy project implementation	=	
Urban development and sectoral plan implementation				
Urban development and sectoral plan monitoring and management	+	Energy consumption monitoring and management	=	Energy-integrated urban development plan management

in developing countries. Energy policies in cities should include energy conservation and efficiency as immediate solutions to increasing energy demands, whereas a change in the local energy matrix towards greater use of renewable energy could be a strategy for the long-term [55]. Tables 6 and 7 show factors that are key to integrating energy strategies with land use planning activities and urban planning, namely: i. Land use and transport planning (trip reduction measures, street design and layout, traffic rules, parking plans and contiguous development patterns); ii. Efficiency in infrastructure (water and wastewater processes, heat and power recovery, and infrastructure planning); iii. Site planning (building design, landscaping, pedestrian facilities and transit facilities); and iv. Energy supply (waste heat utilisation, cogeneration systems, renewable energy utilisation, waste-to-energy systems, and electricity supply and distribution). These elements should be deployed through applicable policies and regulations that allow urban planning, design and implementation to consider the importance of energy and environment issues to achieve sustainable urban development [56].

5. Conclusions

This study analyses the relationship between energy and sustainable development in Bogotá as a case study of a city in a developing country. An analysis and evaluation of energy and sustainable development is important for determining energy solutions that simultaneously drive development and promote economic growth, environmental protection and social equity. Energy demand is determined by the growth in economic activity, the population, the composition of the industry, and living standards.

The data show that the transportation sector is the greatest consumer of energy, whereas the industrial sector has reduced its relative consumption. However, the service sector has increased its share of energy consumption over the last decade in Bogotá.

Bogotá consumes 24% of the electricity of the country. Electricity is the most consumed energy source, followed by petroleum products (gasoline and diesel), coal, and natural gas. The main emissions generated by combustion processes are CO_2, NOx, CO, CxHy, PM and SO_2. Moreover, energy consumption and GDP have increased and slightly decoupled in the last three decades.

Correlation analyses show that higher energy consumption is correlated with a higher population, more industries, higher GDP, more CO_2 emissions and improved HDI values. However, the negative correlation between energy and GINI shows that an increase in energy consumption leads to a decrease in inequality. Similarly, energy intensity measured as energy per GDP, electricity consumption per industry, and tonnes of CO_2 emissions per GDP have a positive correlation; thus, strengthening measures and programs to improve energy efficiency is important.

The relationship between energy intensity and social indicators indicates that higher energy consumption per capita drives higher electricity consumption per capita and improves human development and equality. In contrast, energy intensity and CO_2 emissions per capita are negatively correlated, indicating that improvements in energy use, quality of life and equality are associated with better environmental performance.

These results demonstrate the importance of formulating adequate energy policies that promote sustainable development in cities, which involve the interactions of citizens, government and nongovernmental organisations, and businesses. This complexity requires a diagnosis, analysis and evaluation of the main trends in energy use and CO_2 emissions to define integrated strategies that involve active management, land use planning, new civil infrastructure, energy conservation, energy efficiency and renewable energy.

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