Thermodynamic assessment of Latin American cities applying exergetic efficiency: effects of information availability on efficiency evaluation

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Abstract:

Energetic analysis of cities is a challenging task, due to the lack of a concise, general thermodynamic parameter to evaluate energetic output streams that is applicable to every city. Therefore, exergetic efficiency was applied as a comparative index, given that it encompasses concepts of first and second laws of thermodynamics, thus providing a figure of merit similar to those applied to thermal systems. The proposed concept was employed to assess five metropolitan areas in Latin America: Bogotá, Buenos Aires, Rio de Janeiro, Santiago de Chile and São Paulo. Comparisons among the five cities show a linear trend of increasing per capita CO_2 emissions with increasing *per capita* inlet exergy, as well as the importance of electric mobility to the overall exergetic efficiency. Also noteworthy is the complexity of observing and assessing internal exergetic streams and the evaluation of a usefulness of industrial production in terms of thermodynamic properties. According to the analysis, São Paulo presented the highest exergetic efficiency, 22.43 %, while Santiago de Chile presented the lowest, 17.94 %. This result is somewhat unexpected, since São Paulo is a warmer city, with significant HVAC use during Spring and Summer, but at the same time reflects São Paulo's exergetic data availability, thus allowing a more detailed evaluation.

Keywords:

Thermodynamics of cities; Smart cities; Exergetic efficiency, Data availability.

1. Introduction

Around 5,000 BC the first cities were formed as primitive centers for trade and religious activities [1] and, as time elapsed, certain cities became specialized centers, e.g., Sidon and Tyre, in modern-day Lebanon, which were well established maritime cities circa 2,000 BC. Since then, urban centers evolved as *locus* for several economic activities like shipping, manufacturing, mining, education, finance, health and many others, with capitals and metropolitan areas being relevant in one or more of these economic sectors. According to the United Nations [2], in 2014, urban dwellers were 54 % of the global population, and this share is projected to be 66 % by 2050. Such an increase in urban density will demand better solutions for mobility, water supply, and waste management, all of which are related to energetic and exergetic efficiency and sustainable development.

Eger [3] and Susanti et. al. [4] pointed out that only in the last four decades have cities been analyzed from a multidisciplinary perspective, instead of being an exclusive subject of demography, and, currently, economic discussions involving concepts such as circular economy [5-7] provide additional tools for the study of cities. Beyond these views in terms of economic roles and sectors, cities can also be seen as living organisms that consume and discard mass and energy, thus being amenable to the laws of conservation which underpin the science of thermodynamics.

Issues with municipal solid waste (MSW) and sewage management are much older than the formal statements of mass and energy conservation, which may help explain why these problems are seldom investigated from a thermodynamics standpoint. Though the number of studies exploring thermodynamics of cities increased in recent years, such assessments are sparse compared to analysis focused on Information and Communication Technology (ICT), which is one of the features of so-called Smart Cities (SC). The

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concept of Smart City is not unequivocal [8,9] but there is consensus regarding the key role of ICT, Artificial Intelligence (AI), and Internet of Things (IoT) to enhance governance, transparency, and mobility, among other interactions of citizens with the urban environment. Albino et. al. [9] argue that a comprehensive approach to SC must also include personal and community needs, considering sustainability in a broader sense. Also relevant is the role of renewable energy, distributed generation and electrical mobility, aiming to improve exergetic efficiency and to achieve net zero emissions.

1.1. Thermodynamic assessment of cities

In this subsection a brief overview of recent studies regarding thermodynamic assessments of cities is provided. Pelorosso et al. [10] presented a discussion involving the concepts of circular economy, low-entropy city and complex socio-ecological systems. The authors also discuss the role of urban green infrastructure (UGI) to increase exergetic efficiency and the possibility of devising a generic strategy applicable to every city. Purvis and Mao [11] examined the application of entropy as an indicator of urban sustainability, by means of assessing exergy and generation of irreversibilities. Cities were analyzed as dynamic entities consisting of dissipative structures, thus showing the limits of a straightforward evaluation of entropy in urban systems. The authors argued that it is not possible to use entropy to assess material flows and degradation in a meaningful way, given the absence of ‘utility’ or ‘usefulness’ metrics in thermodynamics, which only has exergy, that corresponds to energetic availability. Regardless, Purvis and Mao agree with the use of exergetic assessments and circular economy strategies to improve urban sustainability.

Bristow and Kennedy [12] presented a nonequilibrium thermodynamics evaluation based on the concept of dissipative structures as stated by Kondepudi and Prigogine [13]. The authors conducted a macro-scale analysis, presenting results of energetic intensity as function of population density for 22 global cities. Results showed that energy intensity increases at a higher rate than population growth, which is a characteristic behavior of dissipative structures. Additionally, Bristow and Kennedy emphasized the need for further studies, with a consistent methodology, to assess exergetic flows in cities, especially regarding micro-scale processes occurring within their control volume.

Regarding Smart Cities, Zheng et al. [8] reported a scientometric review of smart city literature between 1990 and 2019, encompassing 7,380 articles. Publications were classified according to Web of Science criteria, with 35.05 % of studies being in the ‘engineering electrical electronics’ area, 21.98 % in ‘computer science information systems’, 20.18 % in ‘telecommunications’, and 19.95 % in ‘computer science theory methods’, with no category dedicated to thermodynamics. Yu and Zhang [14] evaluated the energetic efficiency in 251 Chinese cities, given their adoption of smart city policies, between 2003 and 2016. The authors developed a non-convex metafrontier data envelopment analysis to examine energy consumption data, but no analysis of thermodynamic behavior was conducted. Yu and Zhang claim to present the first systematic analysis of energetic efficiency of cities in China and concluded that the adoption of SC policies positively affected energetic efficiency.

Hartmann et al. [15] assessed the exergetic efficiency of a coastal city in Brazil (Florianópolis), focused on the effect of MSW management, showing that a proper waste separation combined with waste-to-energy generation could increase exergetic efficiency by 1.5 %, resulting in a yearly mitigation of 15,761 tons of carbon dioxide. Hartmann and Garcia-Acevedo [16] further developed the methodology for evaluation of the exergetic efficiency of urban centers, presenting results for five cities with different main economic sectors: electricity generation (Foz do Iguaçu), manufacturing (Ingolstadt), services/ICT (Florianópolis), tourism (Hawaii), and oil refining (Singapore), the latter also being a Smart City. The results indicate a linear trend of increasing per capita CO_2 emissions with increasing per capita production of MSW. Also noteworthy is the impact of electric mobility to reduce exergy destruction within the city.

Given this brief overview, the present paper aims to add to the scientific literature by reporting an assessment of the exergetic profile of five major cities in Latin America, thus providing subsidies to improve their exergetic performances. Additionally, it intends to compare and discuss the influence of available data on exergetic evaluation of the cities, given that availability of reliable data is one of the key issues of smart cities [3,4,8,9,14].

2. Theoretical background

Among the reasons to employ exergetic efficiency as an ‘energy smartness index’ one can emphasize that i) it encompasses both the first and second laws of thermodynamics; ii) it can be related to carbon dioxide emissions and fuel savings; iii) it is a positive number between zero and one, thus easy to communicate. Purvis and Mao [11] pointed out that an energetic efficiency analysis based only on the first law of thermodynamics is not adequate to every urban center, given the impossibility to evaluate the ‘usefulness’ of intangible products such as software and services. On the other hand, every city consumes exergy through

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internal irreversibilities, thus it is possible to apply exergetic assessments regardless of the main economic sector.

The thermodynamic analysis applied here involves: a) definition of the metric to be evaluated; b) setting of adequate control volume; c) description of simplification hypothesis; d) mathematical model; and e) analysis of results. The preceding sections have shown that exergy is the thermodynamic property that fulfils a). Regarding b), a proper control volume, which includes streams of energy, enthalpy, entropy, exergy, heat, mass, water, pollutants, among others, is illustrated in Fig. 1.

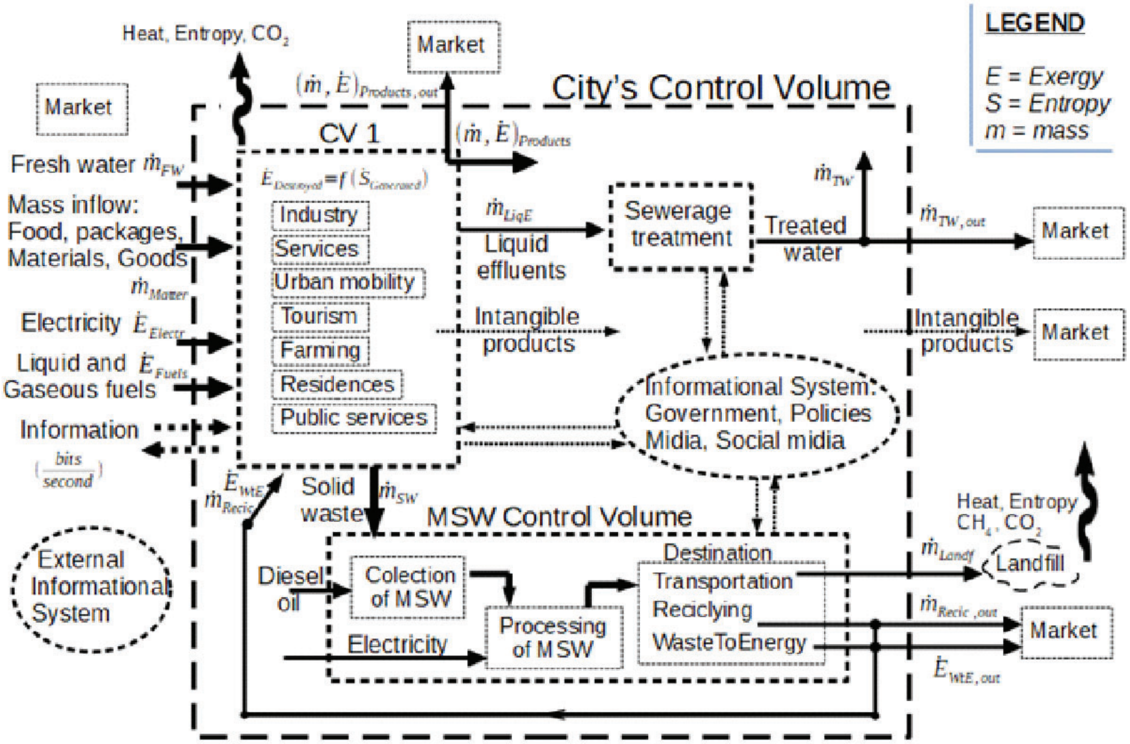

Fig. 1. Representative control volume for the thermodynamic assessment of cities.

The proposed simplification hypothesis are as follows:

(i) Inlets and outlets are considered in terms of yearly average, steady-state streams of exergy;
(ii) Exergy streams are limited to the concepts presented in Hartmann et al. [15], Moran et al. [17] and Szargut et al. [18], i.e., exergy related to altitude, kinetic exergy, electrical exergy, physical exergy related to temperature difference, and chemical exergy (heating value of fuels);
(iii) Vehicles, house appliances and other equipment are considered in terms of annual exergy consumption;
(iv) Analysis will be limited to classical thermodynamics, thus information streams will not be assessed.

2.1. Mathematical formulation

Given the proper control volume and the set of hypotheses, the mathematical model can be formalized. Exergetic efficiency is calculated in terms of inlet and outlet streams,

$$\eta_{II}=\frac{\dot{E}_{out}}{\dot{E}_{inlet}} \qquad (1)$$

$$\eta_{II}=1-\left(\frac{\dot{E}_{dest}}{\dot{E}_{inlet}}\right) \qquad (2)$$

where η_{II} is exergetic efficiency, $\dot{E}_{out}$ is produced exergy, $\dot{E}_{inlet}$ is inlet exergy and $\dot{E}_{dest}$ is exergy destroyed within the control volume. Equation (1) is convenient for evaluating cities which export exergy, like ones with an oil refinery or a power plant, while Eq. (2) shows a general case. The inlet rate of exergy, $\dot{E}$, is simply the sum of all exergetic streams, e.g. electricity, coal, oil, liquid and gaseous fuels, as well as river streams. The exergy rate for electricity is equal to its power, while that for water and other mass streams includes kinetic exergy, physical exergy due to temperature difference in relation to a dead state, and potential exergy [17]. Chemical exergy of liquid and gaseous fuel is calculated following Szargut et al. [18],

$$\dot{E}_{fuel,i}=\dot{E}_{chem}=\beta_{fuel,i}\cdot LHV_{fuel,i} \qquad (3)$$

where $\dot{E}_{chem}$ is the rate of chemical exergy, LHV is the lower heating value, and β is the ratio of chemical exergy to LHV, which is given by Rakopoulos and Giakoumis [19], for liquid and gaseous fuels, respectively, as,

$$\beta_{liq}=1.0334+0,0144\left(\frac{H}{C}\right) \qquad (4)$$

$$\beta_{gas}=1.0334+0,0144\left(\frac{H}{C}\right)-0.0694\left(\frac{1}{N_C}\right) \qquad (5)$$

where H/C is the hydrogen to carbon ratio in the fuel, and N_C is the number of carbon atoms in the fuel molecule. Exergy outlet evaluation is analogous to the exergy inlet one, plus the streams of wastewater and MSW, when useful data is available. The evaluation of the rate of exergy destruction is expressed as,

$$\dot{E}_{dest,i}=\left(1-\eta_{II,i}\right)\dot{E}_{Inlet,i} \qquad (6)$$

where $\eta_{II,i}$ is the exergetic efficiency of a process i. Representative values of exergetic efficiencies of processes and appliances, as well as the source of data are presented in Tab. 1.

Table 1. Exergetic efficiencies for processes and appliances

Process/Appliance	Exergy type	%	Reference
Motors (industrial, mobility)	electric	76.00	[20,21]
Air conditioner	electric	01.90	[22]
Personal computer	electric	75.00	[22]
Lighting	electric	20.00	[22]
Refrigerator	electric	07.20	[22]
Cooking oven	electric	24.20	[22]
Television	electric	80.00	[22]
Vacuum cleaner	electric	70.00	[22]
Water heater	electric	10.50	[22]
Heater/boiler	combustion	06.00	[23]
Internal combustion engines/vehicles	combustion	25.00	[19,20]
Ovens	combustion	14.88	[24]
Combustion/chemical reactions	combustion	70.00	[25]

Assessment of carbon dioxide emissions due to combustion considered stoichiometric combustion [26] with dry air, thus the emissions, in kilograms of CO_2 emissions per kilogram of fuel, are: 3.09 for gasoline, 3.12 for Diesel oil, 1.91 for hydrated ethanol, 3.02 for liquefied petroleum gas (LPG), and 2.75 for natural gas. Emissions from coal, when necessary, were obtained from data available for each analysed city.

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3. Results and discussions

The proposed methodology [16] was applied to assess five global cities in Latin America: Bogotá, Buenos Aires, Rio de Janeiro, Santiago de Chile and São Paulo. The selection of these cities considered their presence in the IMD-SUTD Smart City Index Report 2021 [27], and the energy data used as input for the present analysis were obtained from their respective open data/transparency websites and reports, which are referenced in each subsection. However, the availability and specificity of municipal data varied significantly between cities, thus hampering a thorough assessment. In order to check the reliability and consistency of some metrics calculated in the present assessment, like per capita emissions, data available at the US Energy Information Agency [28], the Our World in Data Project [29] and the International Energy Agency [30] served as baseline values. Each of the following subsections provides details regarding these differences of available information. The analysis was carried out based on data of the year 2019, before the Covid-19 pandemic.

3.1. Bogotá

Bogotá is the capital and largest city of Colombia, with 7.2 million inhabitants in the city proper (Geoportal del DANE - Geovisor CNPV 2018) and 10.7 million in the metropolitan area. The urban centre covers 307.3 km², resulting in a population density above 24,000/km². Bogotá is located in a high plateau of the Andes, with an average altitude of 2,640 metres and typical temperatures between 5 and 20 °C. The metropolitan region is responsible for 24.7 % of national gross domestic product and the El Dorado International Airport handles the largest cargo volume in Latin America.

According to the Smart City Index [27], Bogotá ranks 116 out of 118, with a ‘D’ rating, in a tier shared with Nairobi, Lagos, Rio de Janeiro and São Paulo. Energy and emissions data for Bogotá are available on open data websites <http://www.sui.gov.co/web/energia> [31] and <https://public.tableau.com/app/profile/upme> [32]. It is worth noting that the website hosted by the government [31] has many features, allowing detailed searches considering income level (in Spanish, *estrato*), rural and urban locations, government buildings, and many others. On the other hand, the website was frequently offline, usually at night and during weekends. Table 2 summarizes the results of the exergetic assessment of Bogotá.

Table 2. Exergetic assessment of Bogotá, year 2019.

Energy source	Exergy input, TJ/yr	Exergy destroyed, TJ/yr	$CO_{2,\ equi}$, Mton/yr
Gasoline	30,552.7	22,761.8	2.253
Diesel oil	33,926.1	25,274.9	2.353
Ethanol	416.1	310.0	0.028
LPG	1,765.4	1,502.7	0.109
Natural gas	25,201.8	23,689.7	1.844
Electricity	27,273.7	24,137.2	1.287
Total	**119,135.8**	**97,676.3**	**7.874**
Exergetic efficiency	**18.01 %**	**$CO_{2,\ equi}$, ton/person-yr**	**1.096**

From data on Tab. 2, one can notice how the inhabitants of Bogota have an almost equal reliance on gasoline and Diesel for urban mobility, as well as a limited use of LPG. It is important to note that per capita emissions available elsewhere [29] include all emissions sources. In the case of Colombia, more than 50 % of emissions are associated with land-use changes and agriculture, which are not included in our assessment.

3.2. Buenos Aires

Buenos Aires is the capital and largest city of Argentina, with 2.9 million inhabitants in the city proper and 12.8 million in the metropolitan area. The city covers 20,300 km², resulting in a population density above 14,000/km². The metropolitan area has Argentina’s two main maritime ports and represents around a quarter of the country’s gross domestic product. Buenos Aires has a humid subtropical climate, with typical temperatures between 10 and 25 °C, though summers have highs above 35 °C and record highs reaching 43 °C, while record lows are near -5 °C.

According to the Smart City Index [27], Buenos Aires ranks 98 out of 118, with a ‘CC’ rating, in a tier shared with Mumbai, Jakarta, Istanbul, Lisbon, and Budapest. Energy and emissions data for Buenos Aires are supposedly available on open data website <estadisticaciudad.gob.ar>, though it has been down/inaccessible for several months. Therefore, the authors had to use national level data [33-36] to evaluate municipal values, which is likely to produce biased results. Table 3 presents the exergy assessment for Buenos Aires.

Table 3. Exergetic assessment of Buenos Aires, year 2019.

Energy source	Exergy input, TJ/yr	Exergy destroyed, TJ/yr	$CO_{2,\ equi}$, Mton/yr
Gasoline	16,458.6	12,261.7	1.214
Diesel oil	22,478.9	16,746.8	1.559
LPG	2,463.0	2,096.5	0.153
Natural gas	71,949.8	61,229.3	5.265
Electricity	31,880.5	23,910.4	3.099
Total	**145,230.8**	**116,244.6**	**11.290**
Exergetic efficiency	**19.96 %**	**$CO_{2,\ equi}$, ton/person-yr**	**3.690**

From the data in Tab. 3 one can notice Buenos Aires', hence Argentina's, reliance on natural gas, which corresponds to 64 % of the electric mix [29]. It is also noteworthy that about 1.72 million vehicles in Argentina, roughly 17 % of the passenger fleet, are fuelled by compressed natural gas (CNG). Electricity generation in Argentina consumed approximately 590,000 TJ of natural gas in 2019, followed by industries, with a consumption close to 523,000 TJ [34]. Regarding emissions, the electricity generation in Argentina is more carbon intensive than natural gas burning for final uses.

3.3. Rio de Janeiro

Rio de Janeiro is the second-most populous city in Brazil, with a population of 6.72 million, while its metropolitan area is home to 12.28 million. The city proper covers 1,221 km², with a population density around 5,500/km². The city is known for its tropical, humid climate, with daily means above 20 °C, record lows around 10 °C and record highs above 42 °C, thus having significant demand for HVAC.

According to the Smart City Index [27], Rio de Janeiro ranks 118 out of 118, with a 'D' rating, in a tier shared with Nairobi, Lagos, Bogotá and São Paulo. Energy and emissions data for Rio de Janeiro were obtained from its open data website <www.data.rio> [37] and also from state level data [38]. The Data Rio website is not user friendly, since it does not offer data visualization on graphs or tables online, thus working more like a repository of spreadsheets. Table 4 presents the exergetic assessment for Rio de Janeiro.

Table 4. Exergetic assessment of Rio de Janeiro, year 2019.

Energy source	Exergy input, TJ/yr	Exergy input, %	Exergy destroyed, TJ/yr	$CO_{2,\ equi}$, Mton/yr
Gasoline	23,451.4	15.6	17,471.3	1.729
Diesel oil	24,575.5	16.3	18,308.8	1.704
Ethanol	6,936.1	4.6	5,167.4	0.468
LPG	5,568.1	3.7	4,739.6	0.345
Natural gas	35,575.0	23.6	26,532.3	2.603
Electricity	54,453.6	36.2	51,186.4	2.508
Total	**150,559.8**	**100.0**	**123,405.7**	**9.357**
Exergetic efficiency	**18.03 %**		**$CO_{2,\ equi}$, ton/person-yr**	**1.393**

Regarding data on Tab. 4, it is important to note that Brazilian gasoline, available at the pump, is mixed with ethanol, in proportions up to 27.5 %. Hydrated ethanol is also available in gas stations, and most passenger vehicles produced in Brazil since 2006 can run on any mixture between E20 gasoline to E100. Also noteworthy are the low emissions associated with electricity, which are due to Brazil's reliance on hydropower.

3.4. Santiago de Chile

Santiago is the capital and largest city of Chile, and its population of 6.3 million people corresponds to some 32 % of the country. The city has an area of 641 km² with a population density close to 10,000/km². Santiago is located in a valley, with an average elevation of 570 metres, and has a cool, semi-arid climate, with daily averages between 7 and 21 °C, record lows below -5 °C and record highs around 40 °C. According to the Smart City Index [27], Santiago ranks 110 out of 118, with a 'C' rating, in a tier shared with Cape Town, Bucharest, Sofia, Mexico City, Athens, and Rome.

Energy statistics for Santiago de Chile and its metropolitan region are available in reports [39] and on an open data website <energiaregion.cl> [40], which is very user friendly even though it mostly presents per

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capita data, thus lacking the extensive searching features of its Colombian counterpart. Table 5 presents the exergetic assessment for Santiago.

Table 5. Exergetic assessment of Santiago de Chile, year 2020.

Energy source	Exergy input, TJ/yr	Exergy destroyed, TJ/yr	$CO_{2,\ equi}$, Mton/yr
Gasoline	50,141.0	37,355.0	3.697
Diesel oil	53,816.3	40,093.1	3.732
LPG	22,839.1	19,440.6	1.415
Natural gas	25,201.8	23,689.7	1.844
Electricity	64,317.0	56,920.5	19.777
Total	**216,315.2**	**177,499.0**	**30.465**
Exergetic efficiency	**17.94 %**	**$CO_{2,\ equi}$, ton/person-yr**	**4.859**

From Tab. 5 one can notice that Santiago, in comparison with Rio de Janeiro, has a similar population, but its population density is 80 % higher than Rio's and its exergy input is 43 % higher. Per capita emissions are quite high since half of the Chilean electricity generation comes from fossil fuels (22 % coal, 15 % oil, and 14 % gas) [29,30].

3.5. São Paulo

São Paulo is the largest city in Brazil and the Southern Hemisphere, with 12.4 million inhabitants and a population density of 8,000/km². The city comprises around 5.8 % of the country's population but it represents some 10.7 % of the national GDP. São Paulo is located on a plateau close to the Atlantic Ocean, with an average elevation of 800 metres, and has a humid subtropical climate, with daily averages between 12 and 30 °C, record lows around 0 °C and record highs around 40 °C.

According to the Smart City Index [27], São Paulo ranks 117 out of 118, with a 'D' rating, in a tier shared with Nairobi, Lagos, Bogotá and Rio de Janeiro. Energy statistics for the city of São Paulo are available on the São Paulo state open data website [41], though only as a repository for reports and spreadsheets. Table 6 shows the exergetic assessment of São Paulo.

Table 6. Exergetic assessment of São Paulo, year 2019.

Energy source	Exergy input, TJ/yr	Exergy input, %	Exergy destroyed, TJ/yr	$CO_{2,\ equi}$, Mton/yr
Gasoline	61,789.5	20.0	46,033.2	4.556
Diesel oil	64,263.1	20.8	47,876.0	4.456
Ethanol	56,944.7	18.4	42,423.8	3.842
LPG	13,907.9	4.5	11,838.4	0.862
Natural gas	19,753.5	6.4	14,738.6	1.446
Electricity	92,516.0	29.9	76,912.7	4.221
Total	**309,174.7**	**100.0**	**239,882.7**	**20.828**
Exergetic efficiency	**22.43 %**		**$CO_{2,\ equi}$, ton/person-yr**	**1.707**

Regarding data on Tab. 6, it is noteworthy the relevance of ethanol in the São Paulo energy mix, due to the state being Brazil's largest producer of sugarcane, thus making E100 price competitive with gasoline.

The state government of São Paulo publishes monthly data of its energetic profile, which allows more comprehensive analysis compared to the other four cities. Table 7 shows a detailed exergetic profile of natural gas use and Tab. 8 shows a detailed exergetic profile of electricity consumption in São Paulo for the year 2019.

Table 7. Exergetic assessment of natural gas utilization in São Paulo, year 2019.

Energy source	Exergy input, TJ/yr	Exergy input, % of city	Exergy destroyed, TJ/yr
Residential	5,781.8	1.9	5,178.2
Commercial	2,241.9	0.7	1,908.3
Industrial	5,481.9	1.8	3,837.4
Automotive	2,042.0	0.7	1,521.3
Cogeneration	131.7	0.0	52.7
Thermogeneration	4,074.2	1.3	2,240.8

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Table 8. Exergetic assessment of electricity consumption in São Paulo, year 2019.

Energy source	Exergy input, TJ/yr	Exergy input, % of city	Exergy destroyed, TJ/yr
Residential	41,313.5	13.4	37,430.0
Commercial	32,788.1	10.6	28,525.7
Industrial	8,718.0	2.8	2,615.4
Rural	6.8	0.0	2.0
Public lightning	1,643.3	0.5	1,339.3
Public buildings	8,046.3	2.6	7,000.3

It is possible to observe in Tab. 7 that there is no prominent sector using natural gas, since none of them represents more than 2 % of inlet of exergy into São Paulo's control volume. Observation of Tab. 8, on the other hand, reveals that, in the case of electricity use, there are some sectors more suitable for exergetic improvements. Residential and commercial sectors presented higher shares of electricity use, thus offering more opportunities for improvements related to renewable energy microgeneration, wall insulation, smart building management, and general strategies for energy efficient buildings. These initiatives are also applicable to public buildings.

Regarding urban mobility, São Paulo presents a higher share of ethanol use, about 18.4 %, compared to 4.6 % in Rio de Janeiro. On the other hand, Rio de Janeiro has a higher share of vehicular natural gas, about 18.8 %, while in São Paulo it is only 0.7 %. These differences are due to the distinct energetic profile of the states, e.g. São Paulo is the main producer of ethanol, while Rio de Janeiro is the main producer and industrial centre of petroleum and natural gas in Brazil.

Regarding electromobility, both cities present a very low percentage of electric vehicles, lower than 0.05 %. It is important to note that for Rio de Janeiro and São Paulo summation of all fuels for mobility (ethanol, Diesel oil, gasoline and natural gas) is in the range of 55 – 60 %, thus offering a significant room for exergetic improvement by means of electromobility adoption. In fact, this observation is also valid for Bogotá, Buenos Aires and Santiago de Chile. Table 9 presents the comparison of exergetic efficiency, CO_2 emissions and population of the five cities analyzed.

Table 9. Exergetic comparison of the five assessed cities.

City	Population, Million people	Total Exergy input, TJ/yr	Exergetic efficiency, %	CO_2 Emission, Ton/person-yr
Bogotá	7.2	119,135.8	18.01	1.096
Buenos Aires	2.9	145,230.8	19.96	3.690
Rio de Janeiro	6.7	150,559.8	18.03	1.393
Santiago de Chile	6.3	216,315.2	17.94	4.859
São Paulo	12.4	309,174.7	22.43	1.707

In Tab. 9 one can notice that, even though Buenos Aires has less than half of the population of Bogotá, it presents higher input of exergy. Also, comparing the Brazilian metropoles, São Paulo presents noticeably higher exergetic efficiency compared to Rio de Janeiro. The likely culprit for this difference is Rio de Janeiro's warmer climate, which increases electricity consumption by very exergetic inefficient (1.9 %) air conditioners.

3.6. Effects of geographic location and data availability on the calculation of exergetic efficiency

Geographic location has a strong influence on the exergetic performance of cities, mainly due to different HVAC needs of each climate. According to Table 1, comparing electric devices, exergetic efficiency of air conditioners is 1.9 % while for water heaters the value is 10.5 %. For gas boilers applied for water heating, the exergetic efficiency is around three times higher, which means that colder cities are likely to present higher exergetic efficiencies, but the present assessment does not reproduce this expectation. For instance, the exergetic efficiency of São Paulo, located in Köppen's 'Cwa' (dry winter) climate zone, was evaluated as 22.43 %, while Buenos Aires, located in Köppen's 'Cfa' (humid year round) climate zone, has an exergetic efficiency of 19.93 %. This discrepancy could be due to differences in mobility systems, which has been previously observed by Hartmann and Garcia-Acevedo [16] when evaluating the exergetic efficiency of Ingolstadt, Germany, where an extensive system of electric trams operates. However, in the current

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comparison, Tables 3 and 6 shows that Buenos Aires and São Paulo present similar amounts of combustion exergy on their transportation sectors. It is noteworthy that combustion exergetic efficiency of any fuel is almost the same because of the dynamic behaviour of machines for mobility, as pointed out by Rakopoulos and Giakoumis [19]. Thus the unexpected difference in the results for Buenos Aires and São Paulo must be related to a different source of exergy destruction.

One possible reason for such difference could be attributed to errors on data collection and/or miscalculations. In order to check for possible discrepancies, some results were compared to the literature, e.g., Figure 2 shows the plot of *per capita* CO_2 emission as function *per capita* inlet exergy.

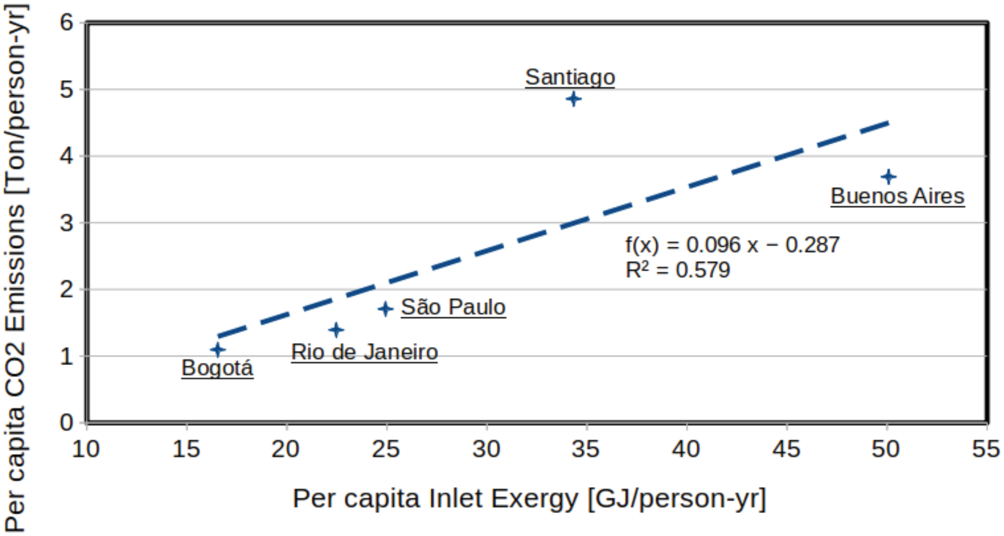

Fig. 2. Plot of per capita CO_2 emission as function per capita inlet exergy.

Figure 2 shows a linear trend of increasing *per capita* CO_2 emission with increasing *per capita* inlet exergy, with a similar trend being reported by Hartmann and Garcia-Acevedo [16]. It is noteworthy that Santiago de Chile presented the highest *per capita* emission of CO_2, of 4.859 Mton of CO_2 per person-year, visible as an 'outlier' well above the trend line on Fig. 2. This high volume of emissions is due to significant consumption of coal and Diesel oil for electricity generation.

Thus, the exergetic efficiency comparison between Buenos Aires and São Paulo, considering their distinct climates, further comparisons with literature data, and with the observed lack of reliable exergetic data for Buenos Aires, as discussed in section 3.2, allows us to conclude that the differences on exergetic efficiency between these two cities is mainly due the lack of comprehensive and reliable exergetic information for the city of Buenos Aires. For instance, data presented on Tables 7 and 8 for São Paulo allowed a better assessment of São Paulo, being on accordance with a previous analysis carried out for a well established Smart City, Singapore [16]. Therefore, one can expect that, as smart grids and smart city initiatives are implemented in the major metropolitan areas of Latin America, it will be possible to improve the quality and thoroughness of this kind of exergetic assessment.

4. Conclusions

An exergetic assessment of five Latin American cities was carried out by comparing their inlet and outlet exergetic fluxes and then calculating the exergetic efficiency and carbon dioxide emissions in CO2 equivalent ton by person per year.

The methodology for evaluation of the exergetic efficiency of urban centers takes as a metric to be evaluated the major energetic fluxes, i.e. gas and liquid fuels as well as electricity; it assumes the city border as a control volume; applies the mathematical model developed by Hartmann and Garcia-Acevedo [16], which follows the basic principles for the evaluation of machines and thermal systems, resulting in an overall exergetic efficiency for each analised city.

São Paulo, rated "d" in the smart index, has the highest exergy efficiency among the cities studied, 22,43%. This result is likely due to the highest participation of ethanol in its mobility-related consumption, since ethanol's share is of the same order of magnitude as gasoline and diesel, as shown on Table 6. Other cities also rated "d" in the smart index, as Bogotá (18,01%) and Rio de Janeiro (18,03%), have medium value of exergy efficiency. On the other hand, Santiago de Chile has the lowest exergy efficiency (17,94%) and highest carbon dioxide emissions index (30,46 MTon CO2 per year), even though its population is about half of Sao Paulo's. This result is probably due to the low use of ethanol combined with the extensive use of natural gas as a main fuel of the automobile fleet.

It is also possible to observe a relationship between the cities' high temperatures and their low exergetic efficiency. This phenomena could be explained due to the massive use of air conditioning systems while also related to the type of primary source for the electricity production. Such a scenario presents an opportunity to improve the city's Smart City Index, by means of investing, for example, in constructive systems aimed at improving the energy efficiency of buildings. The methodology has been demonstrated to be applicable for an initial assessment of the smartness of cities, but further data granularity is required to provide a thorough analysis.

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