SÃO PAULO STATE EXERGY ANALYSIS

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Abstract. *Energy systems need to be more efficient in order to guarantee a sustainable development in face with the challenges of Climate Change. Exergy analysis is a powerful concept to measure the quality of energy and the irreversibility associated with its use. São Paulo, the most populous and rich state in Brazil, was considered as the region of interest in this present study. The Residential, Commercial and Public and Transportation sectors were evaluated using exergy analysis and their respective energy and exergy efficiencies were calculated. As expected, the exergy efficiency was significantly lower than the energy efficiency. The exergy efficiency was then compared with the existing works available in the literature and it was found that São Paulo's exergy efficiency is well within the range of other regions and countries. The results are useful as a guidance for public policy envisaging a better use of our natural resources in less harmful ways to the environment.*

Keywords*: Exergy analysis, state of São Paulo, efficiency.*

1. NOMENCLATURE

B	exergy (kJ)
b	specific exergy (kJ/kg)
H	enthalpy (kJ)
HHV	higher heating value (kJ/kg)
m	mass (kg)
q	specific heat transfer (kJ/kg)
Q	heat transfer rate (kW)
S	entropy (kJ)
T	temperature (K)
W	Power, shaft work (kW)
w	Specific work (kJ/kg)
Greek Symbols	
γ	exergy grade function
η	energy efficiency (%)
ψ	exergy efficiency (%)
Subscripts	
0	environment
C	commercial-public
c	cooling
ch	chemical
e	electrical
f	fuel
h	heating
m	mechanical drive
o	overall
p	product
R	residential
T	transport
Superscripts	
W	work, shaft work

2. INTRODUCTION

Exergy analysis is applied in the São Paulo State in order to obtain indexes which aims at evaluating the quality in the energy conversion process for the end use in three different sectors: Residential, Commercial and Public and Transportation. As all real processes generate entropy, irreversibility, the loss of exergy, occurs (Kotas, 1995). Exergy can be seen, then, as a measure of "energetic opportunity cost". Once expended it cannot be retrieved to be used again, and work availability is lost. An electrical shower is really efficient in converting electricity into heat, but a quantity of water at 40^{o} C cannot produce much useful work, as opposed to electricity. So the process converts energy of higher grade into a very low one. Therefore, a proper use of our finite resources must take into account exergy efficiencies.

A few studies have been performed for different societies (Reistad, 1975; Rosen, 1992; Schaeffer and Wirtshafter, 1992; Wall et al., 1994 and Utlu and Hepbasli, 2005) and are useful because it takes into account not only the quantity of energy expended, but the its quality as well. Exergy efficiency is an absolute quantity, all the inputs and outputs are in the same Thermodynamic basis, which is the potential to perform work. Thus it is possible to directly compare results between different societies, with different energy matrix and consumption pattern, as it was compiled and discussed by Ertesvag (2001) and Utlu and Hepbasli (2007).

Exergy analysis usually break societies down into many sectors, for each sector uses energy differently. Industrial, utility (energy production), transportation, rural, commercial, public and residential are the most common treated sectors. Sometimes, when energy demand profile is sufficiently similar, sectors are merged, such as the commercial and public ones in this work.

The present analyses indicate that that most irreversibility is found when a higher grade energy (i.e., electricity) is used to produce hot water for showering and cooking, or cooling air relatively close to its mean ambient temperature at the time.

Figure 1 gives São Paulo State's energy profile for the years 2005 through 2014. Values were taken from the Sao Paulo State Energy Balance (SPSEB) for each year. The Industrial sector is responsible for about 40% of the state energy consumption. Due to its greater complexity, though, it will not be treated in this work. The transportation sector is the second one with roughly 35% of the total energy consumption; hence, it will produce the greater impact on the energy and exergy efficiencies. Figure 2 shows the energy consumption profile by source. Oil and derivatives (39,5%), sugar cane bagasse (21,2%) and electricity (20,4%) makes the majority of consumption.

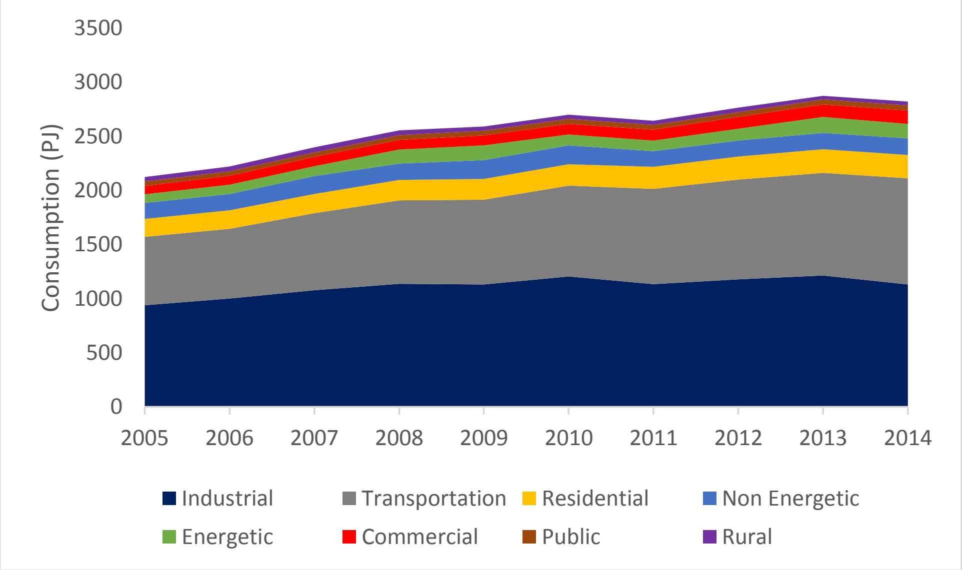

Figure 1. Sao Paulo State Energy Profile 2005-2014 (SPSEB, 2005-2014).

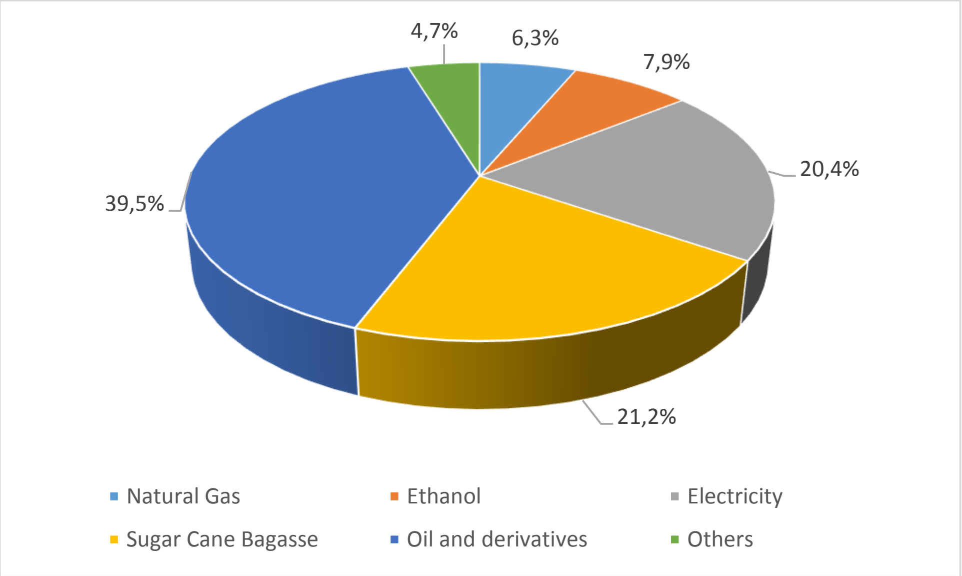

Figure 2. Energy Consumption by (SPSEB 2014).

In this context, the present work is the first attempt to evaluate the efficiency of any State in Brazil, from the Second Law point of view. To this aim, from the available literature data, it was proposed a mathematical model to calculate São Paulo's State energy and exergy efficiencies. Those results should be useful first to show that the exergy are lower than energy efficiencies and second to compare the state's use of its available resources against other societies. It is expected that exergy efficiency be used as a guide to a cleaner, sustainable and efficient energy matrix and society.

3. METHODS

Figure 3 shows the energy flow in a macro system. The selection and possible merging of sectors varies from author to author. This study takes into account only those sectors enclosed by a full line. Those with dotted lines were not treated in the present article.

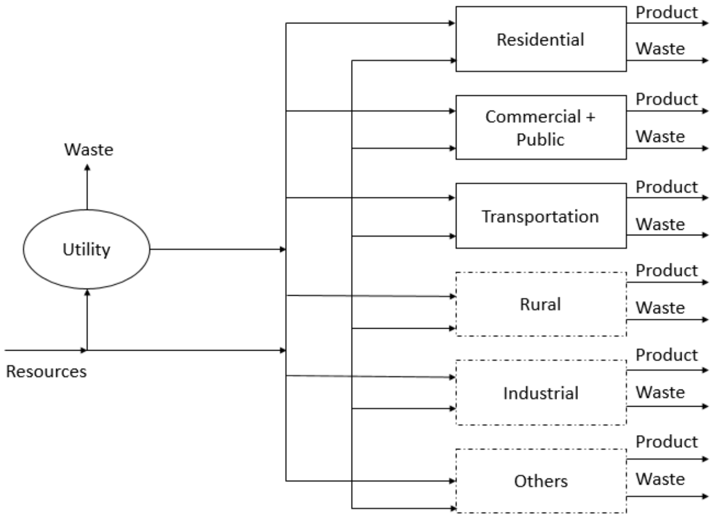

Figure 3. Energy Flows in a macro system, adapted from Rosen (1992).

The exergy balance for a control volume, used to evaluate a macro system, is given by Cespedes and Oliveira-Júnior (1997):

$$\frac{d}{dt}(E + p_0V - T_0S) = \sum_i Q_i\left(1 - \frac{T_0}{T_i}\right) - W - T_0S_{ger} - \left(\sum_s H_s - \sum_e H_e - T_0\left(\sum_s S_s - \sum_e S_e\right)\right) \quad (1)$$

In order to evaluate the adopted control volume, two basic equations were used, regarding the energy and exergy efficiency (Rosen, 1992):

$$\eta = \frac{Energy\ In\ Products}{Total\ Energy\ Input} \quad (2)$$

$$\psi = \frac{Exergy\ in\ products}{Total\ Exergy\ Input} \quad (3)$$

It is important to highlight the difference in applying energy and exergy indexes. The former indicates that the energy is conserved, regardless of its quality or capacity to generate useful work. The latter indicates the capacity of the system to perform some useful effect and its irreversibility. Therefore, when the exergy efficiency is applied, it is possible to compare different energy sources such as heat, electricity, in the same thermodynamics basis, which is capacity of the system to perform useful work.

Heating

Heating is obtained through heat generation Q_p at a constant temperature T_p, the source being either electric energy, W_e, or the burning a mass m_f of fossil fuels. Electrical heating energy and exergy efficiencies are given by (Rosen, 1992):

$$\eta_{h,e} = Q_p/W_e \quad (4)$$

$$\psi_{h,e} = B^{Q_p}/B^{W_e} \rightarrow \left(1 - T_o/T_p\right) Q_p/W_e \approx \psi_{h,e} = \left(1 - T_0/T_p\right)\eta_h \quad (5)$$

For fossil fuel heating generation, the efficiencies are (Rosen, 1992):

$$\eta_{h,f} = Q_p\eta_h/m_fHHV_f \quad (6)$$

$$\psi_{h,f} = B^{Q_p}/m_fb_f \rightarrow \left(1 - T_o/T_p\right) Q_p/m_f\gamma_fHHV_f \approx \left(1 - T_o/T_p\right)\eta_{h,f} \quad (7)$$

Cooling
Not following a more conventional approach based on the coefficient of performance (COP), Reistad (1975) and Rosen (1992) assumed electrical energy efficiencies, $\eta_{c,e}$, as 100%. This work follows the same assumption. For equipment such as air conditioning, freezers and fridges, the exergy efficiency is calculated by Eq. (8):

$$\psi_{c,e} = \left(T_0/T_p - 1\right)\eta_{c,e} \tag{8}$$

Electrical Equipment
For electrical equipment in general, energy and exergy efficiencies were assumed to be 80%, as in Rosen (1992), Utlu and Hepbasli (2005) and the National Institute of Metrology, Quality and Technology (INMETRO), hence:

$$\psi_{h,e} \approx \eta_{h,e} = 0{,}8 \tag{9}$$

For lightning electrical efficiency depends on the technology of each bulb, halogen, incandescent or LED and were obtained at (INMETRO). Exergy efficiency is given by (Rosen, 1992; Utlu and Hepbasli, 2005):

$$\psi_{h,e} \approx 0{,}95\,\eta_{h,e} \tag{10}$$

Fuels – Transportation
For the transportation sector both energy and exergy efficiencies were assumed to be the same (Reistad, 1975; Rosen, 1992), considering the energy grade function of selected fuels, $\gamma_f = HHV/B_{ch} \approx 1{,}00$ (Schaeffer and Wirtshafter, 1992). Following this assumption, the efficiencies are as follows, with the exergy associated with shaft work $B^W = W$:

$$\eta_{m,f} = W/m_f HHV_f \tag{11}$$
$$\psi_{m,f} = B^W/m_f\gamma_f HHV_f\,, with\ \gamma_f = 1, \eta_{m,f} = \psi_{m,f} \tag{12}$$

3.1 Energy consumption and process parameters in different sectors

Data of energy consumption by sector and source was taken directly from the Sao Paulo State's Energy Balance for the years 2005 through 2014, which were treated in this work. Process parameters and data, such as temperatures and electrical efficiencies, were obtained on the literature and INMETRO. Where it was not possible to obtain such data values were assumed.

Residential Sector Energy Consumption
Table 1 gives the energy consumption for the residential sector for the years 2005 to 2014. Liquefied Gas for cooking, responsible for 31,9% on average, and electricity, with 61,7%, were the only sources analyzed, as both combine for more than 90% of total energy consumption.

Table 1. Energy consumption for the residential sector (SPSEB, 2005-2014).

Fuel / Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
LNG (PJ)	61,3	59,7	60,3	62,3	61,9	62,9	60,1	62,4	62,9	58,8
Electricity (PJ)	94,0	99,7	105,7	112,7	118,4	123,2	129,4	135,7	139,6	142,1

Residential Sector Process Parameters
Table 2 gives the energy consumption profile for the residential sector, as well as process parameters to obtain energy and exergy efficiencies, using Eq. (1) through Eq. (12). Device usage percentage was taken from Eletrobrás (2007) and process parameters from (Rosen, 1992; Schaeffer and Wirtshafter, 1992; Utlu and Hepbasli, 2005).

Table 2. Process parameters for the residential sector (Rosen, 1992; Schaeffer and Wirtshafter, 1992; Utlu and Hepbasli, 2005).

Electrical					
		Efficiencies (%)		Temperature (K)	
Device	Usage (%)	η	ψ	T_0	T_p
Fridge	27	100	10,57	293	265
Air Conditioning	11	100	3,14	303	293
Shower	26	95	11,41	293	333
Iron	3	98	30,00	-	-
Lightning	19	15	14,25	-	-
Electrical Appliances	14	80	80,00	-	-
LNG					
		Efficiencies (%)		Temperature (K)	
Device	Usage (%)	η	ψ	T_0	T_p
Cooking Appliances	100	65	16,54	293	393

Commercial and Public Sector Energy Consumption

Table 3 gives the energy consumption for the commercial and public sectors for the years 2005 to 2014. Liquefied Gas for cooking, responsible for 6,7% on average, and electricity, with 84,9%, were the only sources analyzed, as both combine for more than 90% of total energy consumption.

Table 3. Energy consumption for the commercial and public sector (SPSEB, 2005-2014).

Fuel / Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
LNG (PJ)	8,4	8,2	8,2	8,4	8,1	9,5	7,8	9,3	9,7	10,9
Electricity (PJ)	97,8	102,5	107,4	111,5	115,6	120,8	127,4	136,4	139,8	149,0

Commercial and Public Sector Process Parameters

Table 4 gives the energy consumption profile for the commercial sector, as well as process parameters to obtain energy and exergy efficiencies, using Eq. (1) through Eq. (12). Device usage percentage was taken from Eletrobrás (2008) and process parameters from (Rosen, 1992; Schaeffer and Wirtshafter, 1992; Utlu and Hepbasli, 2005).

Table 4. Process parameters for the Commercial and Public sector (Rosen, 1992; Schaeffer and Wirtshafter, 1992; Utlu and Hepbasli, 2005).

Electrical					
		Efficiencies (%)		Temperature (K)	
Device	Usage (%)	η	ψ	T_0	T_p
Air Conditioning	36,7	100	3,14	303	293
Lightning	20,5	15	14,25	-	-
Electrical Appliances	42,7	80	80,00	-	-
LNG					
		Efficiencies (%)		Temperature (K)	
Device	Usage (%)	η	ψ	T_0	T_p
Cooking Appliances	100	65	16,54	293	393

Transportation Sector

Table 5 gives the energy consumption by the transportation sector in each, with fuel type discreminated:

Table 5. Energy consumption by the Transportation Sector (SPSEB, 2005-2014).

Fuel / Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Diesel (PJ)	278,5	267,6	287,4	312,1	312,9	341,2	357,9	378,4	390,3	389,0
Gasoline (PJ)	174,4	175,1	177,7	174,4	164,3	182,4	231,5	269,6	256,5	265,9
Kerosene (PJ)	71,1	67,9	73,1	79,0	78,0	87,9	95,3	97,3	98,2	104,0
Ethanol (PJ)	81,8	108,7	148,1	181,9	209,0	208,2	180,9	161,3	189,7	210,2

Energy and Exergy efficiencies are the same for each fuel type, as Rosen (1992) and Reistad (1975) and are given by Tab. 6. This is the estimated operating efficiency, lower than the rated (full) load for each fuel (Rosen, 1992). Ethanol efficiencies were slightly higher than gasoline, as (Rakopoulos and Giakoumis, 2006; apud Gallo and Milanez, 1992).

Table 6. Energy and Exergy efficiencies of selected fuels (Reistad, 1975; Rosen, 1992; Rakopoulos and Giakoumis, 2006; apud Gallo and Milanez, 1992).

Fuel	**Diesel**	**Gasoline**	**Kerosene**	**Ethanol**
Efficiency (%)	22	22	28	23

4. RESULTS AND DISCUSSIONS

Residential Sector Energy and Exergy efficiencies

Efficiencies were obtained by the weighted mean of the individual device efficiency multiplied by its energy/exergy consumption. Hence, the energy efficiency of electrical devices on the Residential Sector for the year 2014 was calculated as follows:

$$\eta_{r,e} = [(0{,}27 * 1{,}00) + (0{,}11 * 1{,}00) + (0{,}26 * 0{,}95) + (0{,}03 * 0{,}98) + (0{,}19 * 0{,}15) + (0{,}14 * 0{,}80)] = 79{,}7\%$$
$$\psi_{r,e} = [(0{,}27 * 0{,}1057) + (0{,}11 * 0{,}0314) + (0{,}26 * 0{,}1141) + (0{,}03 * 0{,}30) + (0{,}19 * 0{,}1425) + (0{,}14 * 0{,}80)] = 21{,}0\%$$

And the overall efficiencies are given by the weighted mean between electrical and fuel efficiencies and total energy consumption:

$$\eta_{r,o} = (0{,}797 * 142{,}1 + 0{,}65 * 58{,}8)/(142{,}1 + 58{,}8) = 75{,}4\%$$

$$\psi_{r,o} = (0{,}21 * 142{,}1 + 0{,}1654 * 58{,}8)/(142{,}1 + 58{,}8) = 19{,}7\%$$

As stated above, the consumption profile was taken as constant for the years studied, so the electrical and fuel efficiencies would be the same regardless the year. The difference on the overall efficiencies is a result of a different share of electrical and fuel consumption. As such, the overall energy and exergy efficiencies for the Residential Sector are given on Tab. 7.

Table 7. Energy and Exergy Efficiencies for the Residential Sector.

Efficiency / Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
$\boldsymbol{\eta_{r,o}}$	73,9%	74,2%	74,4%	74,5%	74,6%	74,7%	75,0%	75,1%	75,1%	75,4%
$\boldsymbol{\psi_{r,o}}$	19,2%	19,3%	19,4%	19,4%	19,5%	19,5%	19,6%	19,6%	19,6%	19,7%

Exergy efficiency was lower than the energy efficiency. These results are expected, since for house appliances usually don't have great temperature gradients between ambient and end use, thus a low Carnot factor (1 - T_0/T_p) and, consequently, exergy efficiency. The residential sector, then, destroys a great amount of exergy, mainly in converting electricity and fuel into heated water for showering and cooking. Air conditioning and fridges also represented a great proportion of the total irreversibility. Lightning should also shift away from incandescent bulbs to more efficient technologies such as compact fluorescent light bulb (CFL) and light-emitting diode (LED). Solar Energy could also play a role in producing cleaner energy for the residential sector. A study was made to evaluate the economic potential for solar PV generation on residential rooftops in Brazil (Miranda et al., 2015). Policies concerned about rational energy use should, among other factors, focus on reducing exergy destruction and such analysis can be useful.

Commercial and Public Sectors Energy and Exergy efficiencies

The same method for the Residential sector was applied for the Commercial and Public sectors. Both sectors were treated combined, as energy profile and fuel breakdown are approximately the same. The electrical efficiencies are:

$$\eta_{c,e} = (0{,}367 * 1{,}00) + (0{,}205 * 0{,}15) + (0{,}427 * 0{,}8) = 73{,}9\%$$

$$\psi_{c,e} = (0{,}367 * 0{,}0314) + (0{,}205 * 0{,}1425) + (0{,}427 * 0{,}8) = 38{,}2\%$$

And the overall efficiencies are given by the weighted mean between electrical and fuel efficiencies and total energy consumption. For the year 2014, the efficiencies were as follows, and the result compiled on Tab. 8:

$$\eta_{c,o} = (0{,}739 * 149{,}0) + (0{,}65 * 10{,}9)/(149{,}0 + 10{,}9) = 73{,}3\%$$

$$\psi_{c,o} = (0{,}382 * 149{,}0) + (0{,}1654 * 10{,}9)/(149{,}0 + 10{,}9) = 36{,}7\%$$

Table 8. Energy and Exergy Efficiencies for the Commercial and Public Sector.

Efficiency / Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
$\eta_{c,o}$	73,2%	73,3%	73,3%	73,3%	73,3%	73,3%	73,4%	73,4%	73,4%	73,3%
$\psi_{c,o}$	36,6%	36,7%	36,8%	36,8%	36,9%	36,7%	37,1%	36,9%	36,9%	36,7%

The commercial and public sector presented the greater efficiencies overall, with irreversibility found mainly in air conditioning and lightning. Both can be improved by better building envelope, orientation, size and shape, among other factors, and the use of natural resources such as air flows and lightning. These measures could be applied for residential buildings as well (Abanda and Byers, 2016).

Transportation Sector Energy and Exergy efficiencies

The overall efficiencies for the Transportation sector by year, weighed by the share of fuel consumption are given by Tab. 9:

Table 9. Energy and Exergy Efficiencies for the Transportation sector.

Efficiency / Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
$\eta_{t,o}, \psi_{t,o}$	22,8%	22,8%	22,9%	22,9%	22,9%	22,9%	22,9%	22,8%	22,8%	22,8%

The transportation sector is responsible for about 35% of total energy use in the State of Sao Paulo and its efficiency was not greater than 23% for the years considered. From a public policy perspective, the sector presents great opportunities for improvement regarding efficiency and, consequently, green-house gas emissions. Modal shift from individual road to mass public transport as well as policies to improve fuel economy and emissions should be pursued.

Overall Efficiencies

As a result, the overall efficiencies for the sectors considered, weighted by its consumption, are given by Tab. 10.

Table 10. Overall efficiencies

Efficiency / Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
η_o	35,4%	35,7%	35,3%	35,0%	35,2%	35,0%	34,9%	34,9%	35,0%	35,1%
ψ_o	24,2%	24,3%	24,2%	24,2%	24,2%	24,2%	24,2%	24,2%	24,2%	24,3%

Overall efficiencies fall within the range compiled by comprehensive studies done by Ertesvag (2001) and Utlu and Hepbasli (2007). It was slightly higher than that found by Schaeffer and Wirtshafter (1992), which studied the whole of the Brazilian society for the year 1987.

5. CONCLUSIONS

A method to evaluate the energy and exergy efficiency of different sectors was performed in the present analysis, based on literature and energy consumption data of the São Paulo State. Energy efficiencies were about 11% higher than the exergy efficiencies for the years considered, which was expected. Exergy is, then, a better measurement of resource use, for the reasons exposed above. The Residential sector is the one with the least efficient use of resources, mainly for the conversion of electricity into hot water, air conditioning and outdated lightning solutions. Policies should aim at finding ways of making this conversion more efficiently and possibly better explore solar energy. The Commercial and Public sector presented the greater efficiencies. It is advisable, though, that buildings should improve energy efficiency by better use of natural air flows and lightning. The biggest opportunity comes from the Transportation sector, with its high-energy use and low energy and exergy efficiencies. Policies seeking a more sustainable society must pursue better ways for its people to move within, making use of public mass transportation and shift towards more efficient modes. The results should be useful for those concerned about the various ways to obtain and expend energy in a society. Exergy efficiency, thus, is viable indicator of resource use in a society and should help policy makers to make decisions about policy and investment.

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7. RESPONSIBILITY NOTICE

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