What if São Paulo (Brazil) would like to become a renewable and endogenous energy-based megalcity?

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ABSTRACT

This paper analyses São Paulo megalcity’s (Brazil) current and future energy system through the development of an urban energy model, using the Long-range Energy Alternatives Planning System simulation software, covering the period from 2014 to 2030. The paper explores pathways for increasing renewable and endogenous energy resources in the megalcity, reducing its dependency on energy imports and its greenhouse gases emissions. Seven scenarios are modelled considering an integrated multisector energy demand projection that combines energy endogenous potential assessment with improving access of the population to city’ energy services. Currently, São Paulo imports 99% of its energy (% of exogenous resources). In 2030, 31% of endogenous resources can be achieved under a Business as Usual scenario, as well as a reduction up to 43% of greenhouse gases emissions from 2014 levels, by promoting both demand-side and supply-side energy efficiency. When considering better energy services’ access for city inhabitants, accompanied by urban energy policies, a maximum of 25% of endogenous energy share in 2030 and an emission decrease of 24% below 2014 emissions is likely to be reached.

Keywords

Urban Energy System; São Paulo Megacity; Energy Endogenous Potential; LEAP simulation model, urban carbon emissions.

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1. Introduction

Cities are acknowledged as responsible for around 64% of global primary energy use, which accounted for 70% of CO₂ global emissions in 2013 [1]. The cities role becomes even more prominent with the rise of megacities (cities with 10 million or more inhabitants), mainly located in developing countries [2]. Given the magnitude of cities’ impact, urban regions are seen as a potential locus to make the required energy system shift towards decarbonization, increasing energy access to all the urban population, improving inhabitants’ well-being [3], mitigating global emissions, and reducing energy demand through local-scale energy system planning and policy initiatives [4].

Cities have an enormous potential to reduce environmental pressure while enhancing well-being for their inhabitants. This can be made by decoupling cities metabolism from the use of non-renewable energy resources and inefficient processes as part of a transition to a sustainable economy [8], acting on both the demand and supply sides of the Urban Energy System (UES) [5]. According to Rutter and Keirstead (2012), the UES is the combined processes of acquiring and using energy to meet the energy service demands of an urban region [3].

Current scientific literature on UES mostly focuses on some components, as specific economic sectors, or specific end-use energy services, or even specific energy technologies for only one end-use energy service. Regarding the focus on individual economic sectors, examples include works on transports [6] and buildings [7, 8]. Examples addressing specific urban energy end-uses include the focus on urban heat demand [9], building’s heat demand [10] and lighting [11], while works focusing specific technology performance regarding energy savings include smart grids [12], net-zero energy buildings [13], and electric vehicles. Electric mobility in urban areas has had special emphasis, namely on energy management strategies for connecting electric vehicles in urban roads [14], fuel and greenhouse gases (GHG) and other pollutant emission savings for light-duty passenger vehicles [15], and cost-benefit analysis for its deployment [16].

Nevertheless, there are few published studies analyzing the whole UES in an integrated approach. Although there is an increasing number of scientific literature applying optimization energy models at the urban scale, (e.g., [17] analyzing how to optimally integrate renewable energy sources (RES) in UES, or [18] and [19] proposing a bottom-up supply-demand model to assess the optimal performance of UES), there is still lack of literature regarding the use of simulation models of integrated energy system at the city level.

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2In 1950, 38% of the world’s urban population was concentrated in Europe. If North America was added, together these two regions constituted 53% of the world’s urban population. According to the United Nations forecast for world population, in 2050, Asia and Africa will have 73% of world’s population inside its region, and Europe and North America will sum just 15% of the urban population in the world.
Since generally, fossil fuels consumption by cities is acknowledge as a major cause of climate disruption [20], there is a growing interest on increasing cities’ energy self-sufficiency potential by promoting a sustainable energy system transition [21]. However, little is known on current megacities’ UES regarding urban energy demand needs per sector and end-use. Likewise, there is a lack of knowledge regarding megacities’ detailed energy supply profile, and particularly their endogenous potential. In this paper, endogenous energy resources refer to the energy resources available within the perimeter of the considered urban area, that include solar, wind, biomass, local hydro possibilities, waste, industrial heat and power.

In this context, some authors underline the need for integrated urban energy infrastructure planning to better assess the energy supply potential of urban areas [22]. In particular, there is no published work modeling the UES of a megacity using a simulation model, nor addressing how its energy supply and demand can be made more sustainable by harvesting its endogenous RES. This article seeks to fill this gap using a city energy system model for the case study of the São Paulo megacity in Brazil applied for the period from 2014 to 2030.

The Long-range Energy Alternatives Planning System (LEAP) energy simulation model [23] was applied for modelling São Paulo UES in order to characterize the megacity’s current and future energy system concerning energy supply and demand. The model was applied to evaluate possible energy futures, and the goal of the paper is to explore, within the context of a megacity, the possibility for the endogenous and RES energy increase share by 2030 and, by selecting urban energy policies and strategies, simulate the potential for (i) energy savings, (ii) distributed electricity generation increase (by promoting RES and endogenous resources), and (iii) GHG emissions reduction. The paper also provides insights for policy and decision-makers on moving towards a more self-sufficient and socially more inclusive city by explicitly considering improved energy access to 11% of the São Paulo’s population currently living in subnormal housing.

The paper is structured as follows: section 2 describes the methodology used, including basic model description, scenario design, formulation of policy scenarios, and the relevant data used. Results and discussion are presented in Section 3 together with a summary of the main results regarding the city final and primary energy consumption, changes in the urban power sector, GHG emissions reduction and increase in urban RES and endogenous share. Section 4 concludes the paper.
2. Material and methods

LEAP is a widely used energy-economy model both for simulation or optimization purposes. It builds energy scenarios using integrated planning and bottom-up data on energy demand and primary energy transformation (transmission and distribution, primary energy conversion, and energy resource extraction data can be also added). LEAP is flexible regarding its application level, including region, country, state or local level [23]. The model can be used to estimate GHG emissions from energy use and production, emissions of local and regional air pollutants, short-term pollutants, as well as impacts of different policies and measures on GHG emissions, energy savings and local air pollution reduction [23]. More information about LEAP can be found in [24] and [25].

There is a significant scientific production using LEAP within the focus area of this article, as the case of urban passenger transport and the energy and emission reduction potential for Tianjin [26], and the assessment of a range of low carbon policies to project how the city could influence its energy use and its carbon emission from 2000 until 2050 for the case of Bangkok in Thailand [27] and of Ningbo in China [28]. Likewise, LEAP was used to describe Beijing’s future energy strategies for both a BAU pathway of city development and for a scenario considering the impact of policies regarding industry, vehicles and building’s energy efficiency, fuel substitution and transport modal shift [29]. Results show that with the selected policies, the city could reduce energy demand by 55.8% and GHG emissions by 62.2% from 2007 to 2030. Also for the city of Beijing, different methodologies for urban energy modeling (LEAP applied with the following modelling approaches: MARKAL, Input-Output and system dynamics) were integrated within a matrix to ensure a future low-carbon emission energy system while considering economic growth [30].

2.1. São Paulo city LEAP model and data assumption

The LEAP model developed for the city of São Paulo (LEAP_SP) includes three modules: energy supply, energy transformation and end-use energy demand. The following nine economic sectors of the city were considered: (i) Households; (ii) Commerce and Services (C&S); (iii) Industry; (iv) Public Buildings (PB); (v) Public lighting (PL); (vi) Water Treatment (WT), (vii) Energy Sector (ES), which regards the internal consumption of electricity for the activities of transmission and distribution and natural gas for co-generation, (viii) Urban Mobility (UM), and (ix) Air Transport (AT).

The AT sector considers only the Congonhas airport, since Guarulhos’s airport (São Paulo’s international airport) is located beyond the city limits and therefore outside the scope of this study. LEAP_SP time frame is from 2014, Base Year (BY), to 2030, and provides annual results, with no sub-year temporal resolution. Table 1 presents the economic sectors, subsectors, services, end-use technologies, energy resources and carriers considered in LEAP_SP.
In Table 1, the information on the city’s energy services was configured as a % of the population served by each service (i.e. a coverage rate of each service) in the city and was determined according to official data collected from mainly [31–37]. Likewise, information on energy end-use technologies was estimated based on the ownership rates observed in the Southeast region of Brazil, according to data presented in [36]. In 2014 there were around 30 000 industries [38] located in the city. For the purpose of this paper, they were grouped into 3 industrial sub-sectors: Extractive; Transformation and Public Utilities industries. These categories were taken from the [39].
Table 1 - LEAP_SP structure for the energy system demand side

<table>
<thead>
<tr>
<th>Economic Sector</th>
<th>Energy Services/ Subsectors</th>
<th>End Uses/ Technologies</th>
<th>Energy Resources and Carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lighting</td>
<td>Incandescent lamp; fluorescent lamp; LED lamp; lighting kerosene</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Refrigeration</td>
<td>Efficient refrigerators; inefficient refrigerators</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water Heating</td>
<td>Electric boiler; natural gas boiler; solar boiler; LPG boiler</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>Efficient air conditioning; inefficient air conditioning</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Entertainment</td>
<td>TV; radio; laptop</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electronic equipment/devices</td>
<td>Clothes iron; washing machine and other</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cooking</td>
<td>Cooker &amp; stove Liquefied Petroleum Gas (LPG) and Natural Gas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical Transportation*</td>
<td>Lift</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water Pumping*</td>
<td>Efficient pump; inefficient pump</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industry</td>
<td>bExtractive industry</td>
<td>Energy Intensity of each industrial sub-sector (PJ/Gross Value Added)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>bTransformation industry</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>bPublic Utility industry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public Lighting</td>
<td>Lighting</td>
<td>Sodium lamp; mercury lamp; LED lamp</td>
<td></td>
</tr>
<tr>
<td>Water Treatment</td>
<td>Water Distribution</td>
<td>Efficient pump; inefficient pump</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sewage Collection</td>
<td>Efficient pump; inefficient pump</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sewage Treatment</td>
<td>Electronic equipment and machines</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lighting</td>
<td>Incandescent lamp; fluorescent lamp; LED lamp</td>
<td></td>
</tr>
<tr>
<td>Energy Sector</td>
<td>Not specified*</td>
<td>Not applicable</td>
<td></td>
</tr>
<tr>
<td>Urban Mobility</td>
<td>Individual Transportation</td>
<td>Cars and Taxis: gasoline, ethanol, flex (gasoline and/or ethanol), natural gas and electrical; Motorcycle: gasoline</td>
<td>Gasoline Diesel Natural Gas Ethanol Electricity</td>
</tr>
<tr>
<td></td>
<td>Public Transportation</td>
<td>Buses: diesel, ethanol, hybrid (diesel and/or electrical) and electrical; Train and Subway: electrical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-motorized transportation</td>
<td>Active transportation: bicycle and foot</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air Transport</td>
<td>Not specified*</td>
<td>Jet gasoline Jet kerosene</td>
</tr>
</tbody>
</table>

*Applied only for C&S and PB; *No subsector analyses are considered, only aggregate energy consumption data was taken as input for the model.

The models’ key exogenous inputs are energy services and energy end-use for the nine considered economic sectors, plus the technical and economic characteristics of the existing and future energy-related technologies, such as efficiency, availability factor, investment costs, operating and maintenance costs and discount rates. Present and future techno-economic potential of primary energy supply sources (solar photovoltaic, imports of natural gas (NG), micro-hydro, biomass from pruning, municipal solid waste...
or MSW and manure) are also inputs to the model. Final energy imports into the city (electricity, diesel, gasoline, ethanol, residual fuel or residual fuel oil (RFO), kerosene) and policy constraints and assumptions are also taken exogenously. It should be mentioned that, for the case of buildings, different building materials and construction types were not included in the model at this stage, and thus a simplification is assumed.

Figure 1 presents the LEAP_SP model overview, including the key sectors, the main inputs, the macro assumptions that influence directly the energy demand and supply scenarios evolution, as well as the main results. Macro assumptions were determined according to key urban and energy planning issues for the city identified in the base year.

Figure 1 - LEAP_SP model overview
In this paper the city boundaries were defined as the São Paulo administrative region within the São Paulo macro metropolitan region (Figure 2). The LEAP_SP model considers the megacity of São Paulo as a whole, without any intra-city spatial disaggregation into smaller city areas. São Paulo is the largest city in Brazil with 5.9% of the country's population (approximately 11 million inhabitants) [35], the sixth most populous city in the world, and the 3rd largest urban conglomerate of the globe [40] with an urbanization rate of around 99% [35]. The city is a strategic economic hub for Brazil, contributing with almost 12% of the national Gross Domestic Product (GDP) in 2011, and has the largest industrial park in the country.

From 2007 to 2017, the city of São Paulo was the largest electricity and natural gas consumer of the São Paulo state [42–51]. According to the 2010 census, 11% of the city population lives in subnormal dwellings, with very limited access to energy services (e.g. lighting, cooling, cooking, mobility), as well as to water supply and waste collection services [35]. This limited access to energy services highlights the challenges that the city of São Paulo needs to address to make the transition to a more sustainable urban energy system while ensuring enough clean energy resources to improve the quality of life of those inhabitants in particular.
2.2. Supply-side model data inputs

The LEAP_SP model energy matrix characterization for 2014 was based on the available information from the National Electricity Agency database [52]. It includes the electricity generation installed capacity located inside the limits of the city per type of power plant, number of units, total installed capacity (kW) and age, as presented in Table 2. The installed capacity totals more than 900 MW, which delivers 4 TWh annually.

### Table 2 - São Paulo’s city electricity generation installed capacity according to the age of power plants in 2014 [52].

<table>
<thead>
<tr>
<th>Power Plants</th>
<th>More than 20 years</th>
<th>At least 20 years</th>
<th>At least 10 years</th>
<th>&lt; 1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nº. Units</td>
<td>Capacity (kW)</td>
<td>Nº. Units</td>
<td>Capacity (kW)</td>
</tr>
<tr>
<td>Refined Fuel Oil</td>
<td>1</td>
<td>190 000</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Diesel Oil</td>
<td>8</td>
<td>17 407</td>
<td>37</td>
<td>69 233</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>n/a</td>
<td>17 407</td>
<td>37</td>
<td>69 233</td>
</tr>
<tr>
<td>Bagasse</td>
<td>1</td>
<td>27</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Biogas - MSW</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Micro Hydro</td>
<td>1</td>
<td>2 240</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Solar</td>
<td>n/a</td>
<td>n/a</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>209 674</td>
<td>42</td>
<td>77 633</td>
</tr>
</tbody>
</table>

n/a – not applicable

Moreover, the model inputs regarding the RES power plants maximum energy potential considers the addition of a 99 kW biogas biodigester harvesting the city biomass livestock waste; a 3 430 kW biogas biodigester using biomass from pruning, 58 157 kW biogas biodigester using Municipal Solid Waste (considering 3 biodigesters); 120 kW biodigesters from biomass of urban agriculture waste (considering 2 biodigesters); and a maximum possible deployment of 5 180 MW of PV. The data and approach used for estimating the city endogenous RES potential for electricity generation is detailed in Annex A.

23.3. Emission data inputs

LEAP_SP considers the following direct GHG and air pollutant emissions from energy use and generation within the city: particular matter (PM), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), sulphur dioxide (SO₂), aldehydes, nitrous oxide (N₂O), carbon dioxide (CO₂) and methane (CH₄). This means that the model does not consider CO₂ emissions of products and energy carriers imported into the city, except for electricity.
Since this paper considers the energy system inside the city boundaries, it was necessary to model the energy imports into the city. The electricity imported from outside the city boundaries was considered with an emission factor of 0.11 tCO₂/MWh, from the national electricity grid. This value represents the annual average emission factor calculated from 2013 until 2017 [53] and it was assumed constant till 2030, in all scenarios analyzed. Note that, according to the official projections of EPE available in the last National Energy Plans for 2030 and 2050 [54, 55], the share of fossil fuel plants in the electricity system tends to be kept constant until 2030.

24.4. Modelled scenarios design

For the purpose of our analysis, seven scenarios were developed, a Reference scenario (REF) and more six along two main socioeconomic pathways: (i) Business as Usual (BAU) and (ii) Better Energy Services (BET), as presented in Table 3.

The REF scenario was developed for calibration purposes of the LEAP.SP model. The REF scenario does not comprise policies of any kind, and consequently the services share and technology stocks, as well as energy policies till 2030 refer as the base year. The city's energy demand evolution to 2030 in REF was made based on the key assumptions growth rates as in the BAU scenario.

The BAU pathway assumes the current socioeconomic situation with the future evolution following the official energy demand projections supported by variables as: (a) population growth (official projections for the population growth refers to 12.26 million people in 2030 from 11.51 million people in 2014, an average rate of 0.72% per year until 2020 and 0.47% per year until 2030 [56]), (b) expected number of dwellings, (c) evolution of municipal GDP (official projections point to an increase from 628 million R$ in 2014 to 680 million R$ in 2030 [56]), (d) per capita income growth, (e) maintenance of the current rate of access to energy services (i.e. 11% share of population in subnormal dwellings will be maintained), and (f) maintenance of other key assumptions considered for each sector (e.g. evolution of public lighting, public buildings’ area, industry gross value added). All the key assumptions considered in the model to project the city's future energy demand are described in Table 3.

The BET pathway is characterized by higher growth rates than in the BAU pathway of the key assumptions, namely the increase on the access to energy services from the share of the population living under poverty in subnormal houses. Moreover, BET considers the coverage improvement of the city public services that are still not fully provided in the BAU scenario projections, such as the sewage WT coverage rates in the city. Further details on the data for the scenarios are shown in Table 4 and 5.
Table 3- Key assumptions and main data sources for the three pathways REF, BAU and BET

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Households</strong>&lt;br&gt;# dwellings</td>
<td>3.57 million dwellings [57]</td>
<td>4.37 million dwellings</td>
<td>4.76 million dwellings</td>
<td></td>
</tr>
<tr>
<td><strong>Commerce and Services</strong>&lt;br&gt;area (m²)&lt;br&gt;(own calculations based on [44])</td>
<td>105 million m²</td>
<td>110 million m²</td>
<td>114 million m²</td>
<td></td>
</tr>
<tr>
<td><strong>Industry</strong>&lt;br&gt;Industrial GVA (R$)&lt;br&gt;(own calculations based on [57])</td>
<td>66.8 million R$</td>
<td>72.4 million R$</td>
<td>75.9 million R$</td>
<td></td>
</tr>
<tr>
<td><strong>Public Buildings</strong>&lt;br&gt;# buildings</td>
<td>8.45 thousand buildings [47]</td>
<td>8.50 thousand buildings</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Public Lighting</strong>&lt;br&gt;# lamps/devices</td>
<td>560 thousand lamps [58]</td>
<td>663 thousand lamps [58]</td>
<td>768 thousand lamps</td>
<td></td>
</tr>
<tr>
<td><strong>Water Treatment</strong>&lt;br&gt;produced water (m³)&lt;br&gt;(authors assumptions based on [60])</td>
<td>2.1 thousand m³ [59]</td>
<td>2.6 thousand m³</td>
<td>2.6 thousand m³</td>
<td></td>
</tr>
<tr>
<td><strong>Energy Sector</strong>&lt;br&gt;aggregated demand (GWh)&lt;br&gt;(Growing Natural Gas demand 16% per year (based on the analysis of historical series data from [61]))</td>
<td>79 GWh [47]. Decreasing electricity demand 0.8% per year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Urban mobility</strong>&lt;br&gt;# transported passengers&lt;br&gt;(pkm) [51,52,62]</td>
<td>297 billion passenger.km/year</td>
<td>327 billion passenger.km/year</td>
<td>449 billion passenger.km/year</td>
<td></td>
</tr>
<tr>
<td><strong>Air Transport</strong>&lt;br&gt;# transported passengers</td>
<td>18 million (pkm) [43]</td>
<td>26 million (pkm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The base year values were determined according to official and public data like the municipality’s Energy Annuals Statistics Report [49]; São Paulo city Master Plan [33]; São Paulo city Mobility Plan [34]; São Paulo Basic Sanitation municipal Plan [32]; São Paulo city Integrated Plan for Solid Waste management [63]; São Paulo state energy plan [64]; São Paulo state energy matrix [65]; National survey on equipment ownership and usage habits [66]; the national and municipal mobility surveys and mobility reports 2016 [67–70], and the latest national census [35]. Future trends were supported by the national energy plans, and reports and policies [54,55,71–73]. The growth rates for the REF scenario and the two socioeconomic BAU and BET pathways are briefly outlined in Annex B.

Three different scenarios were selected to be simulated for both BAU and BET economic and social pathways scenarios (Table 4), according to the pace of future energy consumption rates:

1) **Historical Trends (H)** - the evolution rate of energy consumption and supply in the city will likely follow the observed historical rates during the period 2007 - 2016. The city energy demand was identified for each sector and energy carrier.
and converted into annualized rates that were reproduced throughout the
modelled period (2014-2030). Historical trends generated the family scenarios
named ‘H’;

2) **Climate Change Policy Goals (C)** - faster energy efficiency deployment rates
were adopted allowing to comply with the Municipal Climate Change Policy
[74] goals. The city will likely reduce the per capita GHG emissions by 30%
below 2003 values (1.25 tCO₂e/inhabitant) [75] until 2030. This scenario family
is designed by ‘C’;

3) **City Endogenous and RES (ERES)** – the city’s endogenous RES potential is
assumed to be deployed through additional policies and measures for both the
demand and supply side, coupled with the faster energy efficiency rates similar
as in ‘C’ scenarios. The ERES scenario simulates the impact of deploying: (i)
PV rooftop potential for the Households and C&S sectors: (ii) potential
generation of biogas from MSW, agricultural, livestock, pruning waste and
green areas maintenance. Regarding the demand side, ERES scenario considers
accelerated technological replacement or substitution through policies and
energy management activities for buildings, urban mobility, and industry sector,
as presented in Table 5. As previously mentioned, endogenous energy resources
are those available within the perimeter of the urban area, both fossil and
renewable.
### Table 4 - Main assumption for the modelled scenarios

<table>
<thead>
<tr>
<th>Drivers/Scenarios</th>
<th>REF</th>
<th>BAU-H</th>
<th>BAU-C</th>
<th>BET-H</th>
<th>BET-C</th>
<th>BAU-ERES</th>
<th>BET-ERES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathways of socioeconomic growth for the city</td>
<td>Evolution according to historical growth rates</td>
<td>Same as REF</td>
<td>Same as REF plus better access to energy/city services(^a)</td>
<td>Same as BAU-H</td>
<td>Same as BAU-C</td>
<td>Same as BAU-H</td>
<td>Same as BET-H</td>
</tr>
<tr>
<td>Energy services rates for non-transport sectors</td>
<td>As disclosed in public database and reports, without increasing access to services. Future rates of services access frozen as in the base year.</td>
<td>Same as REF plus current city policy goals</td>
<td>Same as BAU-H</td>
<td>Same as BAU-H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy services rates for transport sectors</td>
<td>Rates as in 2014</td>
<td>Same as REF</td>
<td>Same as REF plus better access to energy/city services(^a)</td>
<td>Same as BAU-H</td>
<td>Same as BAU-C</td>
<td>Same as BAU-H</td>
<td>Same as BET-H</td>
</tr>
<tr>
<td>Rates of ownership of appliances or technologies in general</td>
<td>Rates as in 2014</td>
<td>Same as REF</td>
<td>Same as REF plus better access to energy/city services(^a)</td>
<td>Same as BAU-H</td>
<td>Same as BAU-C</td>
<td>Same as BAU-H</td>
<td>Same as BET-H</td>
</tr>
<tr>
<td>Annual evolution of final energy intensity of appliances per sector and per energy carrier</td>
<td>As observed from 2007-2016, assumed till 2030</td>
<td>As required to meet municipal Climate Policy. mitigation targets</td>
<td>Same as BAU-H</td>
<td>Same as BAU-C</td>
<td>Same as BAU-H</td>
<td>Same as BAU-C</td>
<td>Same as BET-H</td>
</tr>
<tr>
<td>Technology modifications in energy supply to increase RES and endogenous share of energy</td>
<td>None, as in 2014</td>
<td>Assumed installed capacity reduction compared to 2014 due to the expected end of life of power plants referred in Table 2.</td>
<td>Same as BAU-H</td>
<td>Same as BAU-C</td>
<td>Same as BAU-H</td>
<td>Same as BAU-C</td>
<td>Same as BET-H</td>
</tr>
</tbody>
</table>

\(^a\) The growth rates are improved in such a way that if the city services coverage is still not satisfied by the current policy or historical trend, in the BET scenario it is fully satisfied.
The energy policies in the ‘ERES’ scenarios were primarily targeted for the base year energy city sectors that contribute with the higher share of urban final energy consumption, which is UM and buildings (Households, C&S and PB). Together, these sectors consumed 87% of the city final energy in 2014 (58% in UM, 15% in Households and 14% in C&S and PB) [49]. According to the analysis of the city’s electricity consumption historical data [42–48, 50, 51, 69], a progressive increase was observed in the electricity demand in the building sector, while in industry a significant decrease of consumption in all energy carriers was registered.

The energy policies modelled, as presented in Table 5, were based on the national plans for energy efficiency [54, 65, 78, 79, 70–77] and on international literature [1, 22, 80–82]. They consider an increase in the uptake of efficient technologies, which is the double of observed rates in current policy for São Paulo. For the case of technologies with no policies or targets found in the literature, a 10% growth in technology uptake from 2014 until 2030 was considered. Detailed information on the assumed uptake rates is presented in Annex E.

In the ‘C’ scenarios, improvements in energy efficiency rates by 2030 considered the annualized rates of energy intensity of 0.7% per year to reach 10% electricity savings and 2.2% per year to reach 30% of reduction of fossil fuels consumption and GHG emissions. For the case of public lightning, industry and air transport, such energy efficiency rate improvements would lead to a higher final energy consumption than current trend, due to the current city policy of replacement of mercury and sodium lamps by LEDs and due to the decrease of the industry and air transport activities [85]. Therefore, the historical rates were maintained for those three sectors.

For ‘ERES’ family of scenarios, a package of fifteen energy policies targets was considered as presented in Table 5. These policies consider technological replacement, energy carriers’ substitution and fostering local energy (solar thermal and electricity) generation.
### Table 5- Considered energy and climate policies in the modelled scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>REF</th>
<th>BAU-H</th>
<th>BAU-C</th>
<th>BET-H</th>
<th>BET-C</th>
<th>BAU-ERES</th>
<th>BET-ERES</th>
<th>Economic Sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Assumptions <em>(Table 3)</em></td>
<td>as BY</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>All Sectors</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>All Sectors</td>
</tr>
<tr>
<td>GHG mitigation policy</td>
<td>NO</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>All Sectors</td>
</tr>
<tr>
<td></td>
<td>YES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>All Sectors</td>
</tr>
<tr>
<td>Use of lighting kerosene</td>
<td>as BY</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>Household</td>
</tr>
<tr>
<td></td>
<td>Null</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>More LED- lighting</td>
<td>as BY</td>
<td>NONE</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Households; C&amp;S; PB; IP; WT.</td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>More efficient refrigeration</td>
<td>as BY</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Households</td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>More solar water heating</td>
<td>as BY</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>Households</td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>More NG water heating</td>
<td>as BY</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>Households</td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>More efficient air conditioning</td>
<td>as BY</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Households; C&amp;S; PB.</td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Industrial energy management</td>
<td>With</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>Industry</td>
</tr>
<tr>
<td></td>
<td>Without</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>More efficient water pumps</td>
<td>With</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>C&amp;S; PB; WT.</td>
</tr>
<tr>
<td></td>
<td>Without</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>More electric cars</td>
<td>With</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>UM</td>
</tr>
</tbody>
</table>

---

3 Double growth rate compared to national official governmental forecast [62] reaching a possession rate in 2030 of 5.5% in the Household sector.
<table>
<thead>
<tr>
<th>Scenarios</th>
<th>REF</th>
<th>BAU-H</th>
<th>BAU-C</th>
<th>BET-H</th>
<th>BET-C</th>
<th>BAU-ERES</th>
<th>BET-ERES</th>
<th>Economic Sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>More hybrid buses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UM</td>
</tr>
<tr>
<td>Without</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>as BY</td>
<td>NONE</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fewer losses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Transmission and Distribution</td>
</tr>
<tr>
<td>as BY</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Retrofit old power plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Supply Side</td>
</tr>
<tr>
<td>With</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Without</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endogenous energy sources improvement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Supply Side</td>
</tr>
<tr>
<td>With</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Without</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>More PV - 16.5% rooftops</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Supply Side</td>
</tr>
<tr>
<td>With</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Without</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. Results and discussion

The results gathered from the modelling exercise were analyzed for the seven scenarios using five key performance indicators, pointing to the most relevant aspects of the city energy system performance and characteristics, namely: 1) city final energy consumption (FEC), total and per sector; 2) city electricity generation; 3) city endogenous energy share, considered as an indicator to achieve the city energy self-sufficiency, defined in terms of city local energy carriers (endogenous resource) versus exogenous energy resources (outside city limits, or city imported energy carriers); 4) city RES share, stated as RES consumption versus fossil fuel consumption, and; 5) city emission, stated as GHG emissions per capita. The information referred the base year for the Sao Paulo energy system is presented at the beginning of each subsection, setting a context for the 2030 results.

3.1. City Final Energy Consumption

São Paulo city consumed 367 PJ of final energy in the base year (2014), with the biggest share occurred in urban mobility (58% of FEC, i.e. 211 PJ), followed by the households (15%; 55.9 PJ), and commercial and services (13%; 48 PJ), as illustrated in Figure 3. Regarding urban mobility, the road vehicles presented the highest share of FEC, namely cars (64% of the sector FEC) and buses (32% of FEC). Regarding households, cooking consumed 24% of the sector FEC (13 PJ), followed by water heating (22% of the sector FEC). In the Commerce and Services sector, the largest energy end-use was space cooling, supplied by air-conditioning appliances, representing 37% of the sector FEC (16 PJ) and other appliances with 21% of the sector FEC. More detailed data on FEC is presented in Annex Sections C and D.
Regarding the main energy carriers used in the city in 2014, electricity represented 36% of total FEC (131 PJ), followed by gasoline (92 PJ, 25% of the city FEC), and diesel with 16% of FEC (60 PJ), as illustrated in Figure 4.
The expected FEC in 2030 gathered by LEAP_SP model is presented in Figure 5. Compared with the base year values, the final energy demand is going to increase until 2030 in all scenarios but one (BAU-ERES), between 6% and 130%. Despite this increase, there are some differences in the FEC evolution per scenario that should be underlined. Taking the historic trends of consumption up to 2030, FEC grows 71%-130% in BAU-H and BET-H scenarios, respectively. The difference between BAU-H and BET-H shows that 59% more final energy will be needed if the city becomes more socially inclusive, with better coverage of energy services (e.g. more waste collection, water treatment), while maintaining the historically observed energy demand rates. However, if São Paulo implements a more ambitious energy efficiency rate (i.e. the ‘C’ scenarios), the FEC increase in 2030 is only 6% higher than 2014 values in BAU-C and 45% higher in BET-C. By adopting more endogenous RES, in 2030 BAU-ERES there is a reduction in FEC of 2% compared with the 2014 values, whereas in BET-ERES an increase of 32% FEC is likely to occur. Mobility will continue to be the largest sector regarding city FEC in 2030 in all scenarios, followed by households and commerce and services that keep their relative weight as the second and third largest final energy consuming sectors.

![Figure 5 - São Paulo final energy consumption evolution between 2014 and 2030 by scenario and sector](image)

Table 6 presents results on energy saving per scenario. If São Paulo complies with its Climate Change targets (as in BAU-C and BET-C scenarios), final energy savings in a range between 16% and 38% in 2030 can be achieved in comparison with BAU-H and BET-H, respectively. Moreover, if the city applies additional policies targeting energy efficiency in the demand-side and inclusion of endogenous resources in the supply-side (as in BAU-ERES and BET-ERES scenarios), São Paulo can save up to 23% to 43% of FEC in 2030 compared with BAU-H and BET-H, respectively. ERES scenarios (BAU and BET) present the better energy savings performance, followed by BAU-C and REF.
The ‘C’ and ‘ERES’ families of the BET pathway show a leapfrog performance in 2030 energy savings (when compared with BAU-H) of 16%-23%, respectively, for BET-C and BET-ERES. These scenarios assume the possibility of increasing the city services coverage and access rates while ensuring nonetheless a decrease in energy consumption. However, it is necessary to note that investments in energy efficiency do not necessarily imply a reduction of energy consumption, due to rebound effects [86], and these effects were not considered in the present study. Nevertheless, these results show it is possible to improve the well-being and quality of life of São Paulo citizens without a correspondingly increase in FEC.

Table 6- Final energy consumption savings in 2030: comparison between ‘C’ and ‘ERES’ scenarios with ‘H’ scenarios.

<table>
<thead>
<tr>
<th>Versus</th>
<th>BAU-H</th>
<th>BET-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU-C</td>
<td>38%</td>
<td>No savings</td>
</tr>
<tr>
<td>BET-C</td>
<td>16%</td>
<td>37%</td>
</tr>
<tr>
<td>BAU-ERES</td>
<td>43%</td>
<td>No savings</td>
</tr>
<tr>
<td>BET-ERES</td>
<td>23%</td>
<td>43%</td>
</tr>
</tbody>
</table>

The differences between ‘ERES’ and ‘C’ scenarios are mainly due to: (i) the policies considered in the urban mobility sector of deploying 10% of electric cars and hybrid buses in the city until 2030, and (ii) the replacement of lighting, refrigeration and air-conditioning appliances with more efficient ones on households and commerce and services sectors and, (iii) solely for households, the adoption of more efficient water heating equipment (see Table 5).

As expected, the BET pathways for the city development will likely lead to higher FEC than in BAU and REF scenarios, since BET considers both a wider city services coverage and more people are supplied with these services. However, it is important to note the relevant impact in FEC is achievable with better rates of adoption of energy efficiency equipment. By maintaining current (2014) energy consumption rates (H scenarios), the FEC in 2030 could be 2.3 times higher in the BET scenarios, and 1.7 times higher in BAU scenarios.

In general, the ‘H’ family leads to the highest 2030 FEC in both BAU and BET scenarios. The ‘C’ policies shows the biggest contribution to the reduction of FEC since it assumes higher rates of energy efficient technology uptake. The ‘ERES’ scenarios family leads to the lowest FEC in both BAU and BET scenarios, not only because of the higher rates of energy efficient technology uptake, but also because these scenarios...
additionally consider the effect of increasing local energy electricity production and of a
more ambitious energy and climate policies, as described in Table 5.

Table 7 presents the evolution of the final energy consumption in the city per energy
carrier. It is clear that solar and ethanol increase their consumption share in all
scenarios, while LPG and RFO reduce their relative importance in all scenarios, except
in the REF scenario.

**Table 7- Evolution of final energy consumption in 2030 in comparison with 2014,
per energy carrier for Households, Commerce and Services, Industry, Energy and
Urban Mobility Sectors for the different scenarios.**

<table>
<thead>
<tr>
<th>Carrier/scenario</th>
<th>Households</th>
<th>Commerce &amp; Services</th>
<th>Industry</th>
<th>Energy Supply Sector</th>
<th>Urban Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>22%</td>
<td>63%</td>
<td>32%</td>
<td>163%</td>
<td>117%</td>
</tr>
<tr>
<td>NG</td>
<td>22%</td>
<td>791%</td>
<td>173%</td>
<td>869%</td>
<td>197%</td>
</tr>
<tr>
<td>Kerosene</td>
<td>0%</td>
<td>-88%</td>
<td>-88%</td>
<td>-88%</td>
<td>-88%</td>
</tr>
<tr>
<td>LPG</td>
<td>22%</td>
<td>-7%</td>
<td>1%</td>
<td>12%</td>
<td>-19%</td>
</tr>
<tr>
<td>Solar</td>
<td>22%</td>
<td>293%</td>
<td>251%</td>
<td>327%</td>
<td>282%</td>
</tr>
<tr>
<td>Total</td>
<td>22%</td>
<td>121%</td>
<td>37%</td>
<td>203%</td>
<td>103%</td>
</tr>
</tbody>
</table>

except 2014,
The increase of solar energy is driven by the household’s sector, mainly due to the assumed increase of solar for water heating. In both industry and the energy supply sectors there is a reduction in the consumption of electricity in all scenarios. This is not the effect of any particular policy, instead it results from reducing the city’s economic activity (see section 2.4). In all the other city sectors, there is an increase in the evolution of the consumption of electricity. In the urban mobility sector there is a decrease in NG demand in all scenarios, namely of 84% in ‘H’ scenarios and 98% in ‘C’ and ‘ERES’ scenarios. Gasoline and diesel consumption have a high reduction in ‘C’ and ‘ERES’ scenarios because they are replaced by RES, i.e. ethanol (Table 7).

3.2. City electricity generation

Considering the installed capacity as presented in Table 2, LEAP_SP model calculates the corresponding electricity generation in 2014 within the São Paulo’s city boundaries, as 4 TWh (Figure 6). This represents only 9% of the city’s electricity needs, being the remaining 91% provided by the national grid. This means that the electricity generation within the megacity has substantial room to increase from current values to move towards a higher endogenous UES.

![Figure 6 - Electricity generation in São Paulo city for the REF Scenario (2014-2030)](image)

* values for ‘All others’ and ‘Hydro CHG’ electricity generation were in 2030: 226 MWh and 10 792 MWh respectively.
Whereas the national current electricity generation portfolio has a high RES share [84, 85], the city of São Paulo has a fossil fuel-based electricity generation of around 93%. It is important to note that PV generation in 2014 was almost inexistent in the city. This result contrasts with the recent publication [89] comparing the energy metabolism of the 27 megacities in the world, where a high RES share in the São Paulo electricity matrix is referred. It is worth to note that the authors considered that São Paulo’s electricity matrix has the same mix as the national electricity portfolio and not the currently installed capacity resources that exist within city boundaries. The authors in fact point out this discrepancy as a methodological limitation of their work.

Figure 7 shows how electricity generation compares among the scenarios analyzed. If the old power plants that are close to their end of life (see also Table 2) are phased out, the city’s electricity generation capacity, already low in 2014, will decrease for BAU-H, BET-H, BAU-C, and BET-C scenarios, implying that higher shares of electricity will likely need to be imported from the national grid.

This poses an additional challenge for the megacity regarding the renovation and expansion of its energy supply infrastructure in place, as well as an opportunity for the urban energy system efficiency improvement and endogenous RES promotion. Therefore, in the ‘ERES’ scenarios there is a turning point in the supply infrastructure with a higher uptake of RES in the city’s energy balance. The ‘ERES’ scenarios have an electricity generation growth of 244% (13 TWh) in 2030, when compared with the base year, and the electricity generation are seven times higher than the H and C scenarios’ family. This growth was mostly due to the introduction of PV rooftop, and retrofit old power plants, as shown in Table 8.
Table 8- Contribution of supply-side options to the city's electricity generation, considered in the ERES scenarios

<table>
<thead>
<tr>
<th>Extrapolating the BY situation until 2030 (REF)</th>
<th>Increased electricity generation (TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU-H (2030)</td>
<td>0.4</td>
</tr>
<tr>
<td>plus Retrofit Old Power Plants</td>
<td>3.3</td>
</tr>
<tr>
<td>plus New Endogenous Power Plants</td>
<td>1.7</td>
</tr>
<tr>
<td>plus More PV Rooftop</td>
<td>8.6</td>
</tr>
<tr>
<td><strong>Increased Total</strong></td>
<td><strong>12.4</strong></td>
</tr>
</tbody>
</table>

3.3. City endogenous and exogenous FEC

Regarding the origin of the energy consumed in the city, the endogenous resources represent a small share of the total FEC in the REF and ‘H’ family scenarios. In the base year, only 1% of the total final energy consumed was provided by endogenous sources. Table 9 shows the results regarding the city energy balance for 2014 and 2030 for all scenarios, presented as shares of exogenous and endogenous resources of the total city final energy consumption.
Table 9 - Final energy consumption from endogenous and exogenous energy resources in the city for 2014 and 2030 per scenario.

<table>
<thead>
<tr>
<th>Energy carrier/Scenario</th>
<th>Year</th>
<th>2014</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>REF</td>
<td>BAU-H</td>
</tr>
<tr>
<td>Total FEC (PJ)</td>
<td></td>
<td>423</td>
<td>475</td>
</tr>
<tr>
<td>Total exogenous energy consumption (PJ)</td>
<td>99%</td>
<td>99%</td>
<td>99%</td>
</tr>
<tr>
<td>% [exogenous energy carriers / total exogenous energy consumption]</td>
<td>Electricity (Imported)</td>
<td>35%</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>NG</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>Gasoline</td>
<td>22%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>Jet Kerosene</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Kerosene</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>18%</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>RFO</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>LPG</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>Ethanol</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>Asphalt</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>Jet Gasoline</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Total endogenous energy consumption (PJ)</td>
<td>3%</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>% [endogenous energy carriers / total endogenous energy consumption]</td>
<td>Biogas</td>
<td>71%</td>
<td>53%</td>
</tr>
<tr>
<td></td>
<td>Bagasse</td>
<td>24%</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>Solar (electricity and hot water)</td>
<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Hydro-electricity</td>
<td>2%</td>
<td>1%</td>
</tr>
</tbody>
</table>

Imported electricity has the highest share in the exogenous energy resources and presents the highest share in total FEC until 2030, for all scenarios. Regarding endogenous energy resources, biogas presents the highest share in FEC in 2014, while for 2030 it is expected solar energy will become the most relevant endogenous energy carrier, reaching up to 90% of RES energy carriers in the two ‘ERES’ scenarios. This is due to the expected penetration of solar rooftop options, both PV and thermal, while besides the biogas and bagasse share increase the overall potential, it decreases its total share influence when compared to the biggest growth of PV generation.

These results highlight that there is an untapped endogenous energy potential in the city that is currently being neglected. With the deployment of new biodigester power plants and a conservative estimate for rooftop PV potential, it is possible to increase by around 31% the utilization of endogenous energy resources in the city.
Other important aspect regards the precautionary principle applied to energy dependency. A megacity as São Paulo, so influent and important from the economic and social point of view for the rest of the country, needs to be less energy dependent and vulnerable. When the city increases its endogenous and RES energy in its territory, it is also increasing its capacity to resist to national power blackouts or lack of other energy resources. Moreover, a more self-supporting capacity is also a way of ensuring the minimum provision of key services in the case of a national energy collapse.

3.4. City energy RES

In 2014, 68% of the energy consumed in São Paulo was from fossil sources, as illustrated in Figure 8. The predominance of fossil energy in 2030 is maintained in REF and in the scenarios based on historic rates (BAU-H and BET-H scenarios). In ‘C’ and ‘ERES’ scenarios, fossil fuel consumption is reduced in 2030 by around 50% from 2014 values. The ‘C’ scenarios present the highest shares of RES in 2030 (69-71% of RES in total FEC), making clear the relevance of this type of energy sources to comply with the city’s Climate Change policy mitigation goals.

The significant change in RES adoption occurs in the ‘C’ scenarios due to the consideration of a restriction on the use of fossil fuels in the urban mobility sector. This reflects the existing city’s Climate Policy that proposes a 10% replacement of fossil fuels with RES in the transport sector. It should be noted that the authors extended the proposed assumption for public transport also to private transport in the city.

Figure 8 – Share of fossil and renewable energy consumption for São Paulo, in terms of total final energy consumption.
Regarding electricity generation, Figure 9 shows the increase in installed capacity of the city. This is achieved through the retrofitting of old power plants, through more distributed PV generation, and also by adding new endogenous RES power plants (in the ‘ERES’ scenarios) leading to around 68% more RES in the city’s energy matrix by 2030. The new RES power plants also increase the 2030 electricity generation within the city from around 4 TWh (REF) to 13 TWh (‘ERES’ scenarios) as previously mentioned.

![Electricity generation and RES share for São Paulo per scenario.](image)

**Figure 9 - Electricity generation and RES share for São Paulo per scenario.**

### 3.5. City greenhouse gas emissions

Regarding the city’s GHG emissions in 2014, LEAP_SP model estimated 20 million tCO$_2$e corresponding to 1.8 tCO$_2$e/inhabitant for São Paulo. Note that Brazil’s current emissions per capita are of 1.7 tCO$_2$e/inhabitant [90], revealing a good model calibration. In 2030, the current policy (BAU-H) does not imply any reduction of GHG emissions, instead increases them by around 44% from 2014 values (.).

Table 10. For the case of the improvement of the city’s service coverage rates and access (BET scenarios) and considering no changes in the ambition of energy policies (H scenarios rates), GHG emissions are expected to increase by around 2 times more than in the base year, up to 3.4 tCO$_2$e/inhabitant in 2030. Moreover, when additional policies are assumed to increase the RES and endogenous resources, we may expect a good performance of per capita emission, even in the scenario considering high level of city’s services coverage and access (1.4 tCO$_2$e/inhabitant).

If the city complies with its current Climate Change policy goals (also a municipal law, since 2009), it then could reduce its 2030 per capita GHG emissions by around 38% from base year values for the BAU-C scenario. .
Table 10 shows the best scenario in terms of reduction of the city’s GHG emissions is BAU-ERES (1.0 tCO$_2$e/inhabitant). The ‘ERES’ scenarios results are a consequence of two major factors: (i) the reduction of electricity imports, and (ii) rise of RES endogenous electricity generation.

**Table 10- Total greenhouse gas emissions per sector (Million Metric tCO$_2$e.) in 2014 and 2030 (includes indirect emissions associated with electricity imports)**

<table>
<thead>
<tr>
<th>Year</th>
<th>2014</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>REF</td>
<td>BAU-H</td>
</tr>
<tr>
<td>Total emissions (Million Metric tCO$_2$e)</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>tCO$_2$e/inhabitant</td>
<td>1.8</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Brazil recently adopted the goal of reducing its national GHG emissions by around 37% in 2030 [91] from 2005 values. Therefore, it is expected that the country will move from its current 1.8 tCO$_2$e/inhabitant [90] down to 1.07 tCO$_2$e/inhabitant. Moreover, the Climate Change Municipal Policy of São Paulo [74] aimed to reach in 2012 a reduction of 30% (0.84tCO$_2$e/inhabitant) below 2009 emissions (1.20 tCO$_2$e/inhabitant). This objective was not accomplished, but this law is still in force and has not been updated [74]. If we assume to achieve the 30% of emissions reduction goal by 2030, the only scenario that complies with such reduction is the BAU-ERES, which is a challenge to the expectation of increase the access to energy services by people currently living in precarious conditions.

### 3.6. Summary of results, limitations and main highlights for São Paulo megacity energy transition

The adoption of historic rates of energy efficiency (‘H’ scenarios) led to higher FEC in both BAU and BET pathway. The ‘C’ family scenarios showed the biggest contribution to FEC and GHG emissions reduction, while the ‘ERES’ family presented the best performance regarding the inclusion of endogenous and RES in FEC and the increasing of local electricity generation. Thus, the use of endogenous resources reduced the city energy dependence from 99% in 2014 to 69% in BAU-ERES and 75% in BET-ERES in 2030. BAU-ERES and BET-ERES showed twice as high potential for RES insertion in the city energy balance (from 32% of RES in 2014 to 67% in 2030). The results demonstrate the technical feasibility of achieving 43% GHG emissions reduction in the BAU-ERES scenario, and 24% reduction in BET-ERES compared to the base year.

The REF scenario highlighted the weight of social economic non-development for maintaining energy demand in low levels, while the ‘H’ scenarios showed that current policy ambition levels and uptake rates are not enough to comply with São Paulo’s Climate Change Policy targets. Moreover, a 2015 report of C40 Cities Climate
Leadership [92] (São Paulo is a member) developed climate neutrality scenarios to meet the Paris agreement target of emission reductions\(^4\) until 2020. The report presents what should be a world-wide mitigation effort needed to reduce global warming impacts, and states that cities should contribute with around 40% of the emission reductions needed to achieve the agreed goals, which means to move from an average of 5tCO\(_2\)e per capita today to around 2.9 tCO\(_2\)e per capita by 2030 [92]. Even considering all policies modelled in this exercise, it was not possible to achieve a reduction of 40% in GHG emissions proposed in the report for São Paulo\(^5\).

If the megacity aims to become more inclusive and provide more public services for its population, including energy services, it is a *sine qua non* condition that it should establish higher levels of energy efficiency than those currently achieved. Although ‘C’ policies are important from the perspective of reducing energy demand and emissions, it was assessed that solely improving the energy efficiency uptake rates will not be enough to guarantee a lower energy dependency of São Paulo than the current one. Furthermore, the results regarding the ‘ERES’ scenario policies for the demand side, mostly on technological substitution, showed a small influence on the reduction of the 2030 energy demand: solely around 4% in the BAU pathway (when compared to BAU-C) and only 6% in the BET pathway (compared to BET-C).

The modeling exercise presents some limitations that should be mentioned. It was not considered for PV and solar thermal potential that both technologies may compete for roof space. Other types of endogenous resources such as sewage sludge, industry heat waste and district cooling potential were also not considered in this stage. Moreover, LEAP_SP model represents the aggregated city energy demand and supply evolution without considering São Paulo’s different sub-city areas and neighborhoods, which have different economic, social and energy consumption characteristics, so the results must be approached as aggregated estimates for the city.

Regarding the simulation model limitations, it should be mentioned that some parameters have little robustness due to the limited data available for some of the city’s activities, as it is the case of energy technologies ownership. These parameters are kept constant from 2014 till 2030 and thus can be either under- or overestimated in the long run. LEAP_SP model was developed using the best information available, which dated to 2009 regarding power plant location and energy end-use, technology-related information, and other energy demand drivers. It would be necessary to revisit these data and assumptions when more updated information become available. Finally, like most technology-based models, LEAP_SP does not consider in detail behavior related consumption information (e.g. rebound effect).

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\(^4\) Holding the increase in the global average temperature below 2 degrees above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5 degrees above pre-industrial levels.

\(^5\) Considering the Municipal Climate Change targets that has as BY 2009 emissions. This discussion was previously presented in section 3.5. Plus, it is necessary to take into consideration that São Paulo per capita emission is beyond the median minimum emission per capita presented in the mentioned report.
6314. Conclusion

This article presented the LEAP energy system model for the city of São Paulo (Brazil) and its application to assess possible pathways to change the megacity’s current energy system by 2030. Seven scenarios were modelled considering the urban energy system in a holistic approach and paying special attention to the urban potential for endogenous energy resource use. The article estimates the impacts of each of these scenarios on: (i) energy savings; (ii) share of distributed electricity generation, (iii) potential for increasing RES and endogenous energy city resources, and (iv) local GHG emissions reduction until 2030.

Two pathways of socioeconomic development were considered for the modelled scenarios, BAU versus BET. BAU assumes current rates of access to urban energy services for the São Paulo’s population, whereas BET considers an improvement in energy access rates for 11% of the population currently living in subnormal housing. These pathways have been modelled over seven scenarios, being REF scenario a non-policy scenario; BAU-H and BET-H developed over historic policy rates of energy efficiency deployment and RES technologies; BAU-C and BET-C considered a high energy efficiency pace to reach the Municipal Climate Change Policy goals; and BAU-ERES and BET-ERES, made similar to BAU-C and BET-C, complemented with additional policies to foster usage of endogenous energy resources.

The results show that currently São Paulo imports 99% of its final energy consumption (FEC) (% of exogenous energy resources). The REF scenario keeps this share identical up to 2030, while the BAU socioeconomic pathway scenarios may lower these imports to reach up to 31% of endogenous resources in terms of total FEC. For the BET socioeconomic pathway scenarios, considering higher energy services’ access for city inhabitants, it is possible to reach up to 25% of endogenous resources in FEC in 2030. The variation range in the endogenous resources share depends on the demand-side energy efficiency measures considered and the supply-side efficiency improvement of the local electricity generation.

If historic energy technology deployment rates are maintained (BAU-H and BET-H scenarios) up to 2030, only 40% of RES share in FEC is attained, no energy savings are achieved compared to the base-year (in 2030 São Paulo will have 1.7 to 2.3 times more energy consumption), and the GHG emissions increase by 44% to 91% from 2014 values. This highlights the big gap in the city’s current development pathway regarding ambitious energy and climate targets. With such historic rates it is not possible to comply with the city’s climate goals making clear the need to move faster.

For the other two scenario variants (considering a faster deployment for complying with GHG mitigation targets, named “C” scenarios and for increasing endogenous and RES share, or “ERES” scenarios), it was found that energy savings increase by 37-38%, respectively for BAU-C and BET-C, and by 43% for BAU-ERES and BET-ERES,
compared to BAU-H and BET-H (historic scenarios). Regarding the city electricity
generation, it was found that up to 13 TWh can be generated within the city by 2030
(for BAU-ERES and BET-ERES scenarios). The adoption of RES can be as high as
71% of final energy consumption for the BET-C scenario (69% for BAU-C). Regarding
local GHG emissions reduction until 2030, the best performance was obtained by the
ERES scenarios (BAU-ERES with 43% less GHG emissions from base year levels, and
BET-ERES with 24%).

Considering strictly the energy indicators used in this study, the BAU pathway of city
development shows a better performance than the BET pathway. However, BET
represents a significant increase in the quality of life for many city’s inhabitants and
thus it should be seen as showing that a more sustainable urban energy system is still
possible while improving the well-being of inhabitants and reducing poverty.
Regardless of the socio-economic development pathway (BAU or BET), it becomes
clear that it is necessary to aim for a more ambitious and faster deployment of energy
efficiency and RES to ensure the transition to a more comprehensive and holistic urban
energy policy approach.

This paper illustrated the importance of considering all possible options to improve the
cities’ energy sustainability while improving life conditions for all its residents. As
shown, a sustainable transition is technically feasible. More research is needed to ensure
that it is also economically, legally, politically and socially feasible from a governance
point of view.

Finally, the results highlight that acting based on traditional energy efficiency policies
mainly steering towards technological replacement with more energy efficient
equipment is not enough to significantly reduce megacities' energy consumption and
dependency on exogenous energy resources. In this sense, further work should focus on
the analysis of the potential for energy conservation in urban areas, for example by
integrating urban and energy planning to reduce/avoid increasing megacities’ energy
needs.

5. Acknowledgment

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Mundus, BE MUNDUS Program, and to Fundação de Amparo à Pesquisa do Estado de
Environment Institute for providing enough license time to the development of the
research. Finally, we would like to thank the anonymous reviewers for their helpful
comments.
## Glossary of terms and acronyms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT</td>
<td>Air Transport</td>
</tr>
<tr>
<td>BY</td>
<td>Base Year</td>
</tr>
<tr>
<td>BET</td>
<td>Better Energy Services</td>
</tr>
<tr>
<td>BAU</td>
<td>Business as Usual</td>
</tr>
<tr>
<td>C</td>
<td>Climate Rates</td>
</tr>
<tr>
<td>C&amp;S</td>
<td>Commerce and Services</td>
</tr>
<tr>
<td>ERES</td>
<td>Energy RES and Endogenous</td>
</tr>
<tr>
<td>ES</td>
<td>Energy Sector</td>
</tr>
<tr>
<td>FEC</td>
<td>Final Energy Consumption</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gases</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>GVA</td>
<td>Gross Value Added</td>
</tr>
<tr>
<td>H</td>
<td>Historical Rates</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied Petroleum Gas</td>
</tr>
<tr>
<td>LEAP</td>
<td>Long-range Energy Alternatives Planning System</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal Solid Waste</td>
</tr>
<tr>
<td>NEG</td>
<td>National Electricity Grid</td>
</tr>
<tr>
<td>NG</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PB</td>
<td>Public buildings</td>
</tr>
<tr>
<td>PL</td>
<td>Public lighting</td>
</tr>
<tr>
<td>REF</td>
<td>Reference Scenario</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>RFO</td>
<td>Residual Fuel Oil</td>
</tr>
<tr>
<td>UES</td>
<td>Urban Energy System</td>
</tr>
<tr>
<td>UM</td>
<td>Urban Mobility</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compounds</td>
</tr>
<tr>
<td>WT</td>
<td>Water Treatment</td>
</tr>
</tbody>
</table>

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32
7. References


[2] AEO2016&cases=ref2016-ref_no_cpp&sourcekey=0.


[74] Prefeitura do Município de São Paulo, Política de Mudança do Clima no Município de São


R. Tourte, Plano Municipal de Sanemaneto Básico de São Paulo, II (n.d.).


Data used for estimating the city endogenous potential for electricity generation considered the following energy resources possibilities:

i. **solar rooftop photovoltaic (PV) potential** took into account the city average annual incident solar radiation per season of 4.59 kWh/m².day [93], the available, useful and economically feasible rooftop area of 16.5%, according to [94], from total Trade & Services and Households of 357 million m² considered for the BY [38]. PV efficiency of 16% and System Performance Ratio (SPR) of 80% were taken from [94,95];

ii. **biogas from MSW potential** considered 1.900 t/day of MSW generated in the BY [96,97], from this value it was estimated the methane production from the Volatile organic compounds (VOC) of MSW, considering that one ton of VOC produces about 400 m³ of CH₄, and that methane, in normal conditions, has low calorific value (LCV) of 9.9 kWh /m³, and that the food residues have an average composition of 23% VOC [98,99].

iii. **biogas production from urban agriculture biomass waste** considered the same just mentioned premises that MSW, and the yearly average city food production from perennial and temporary kinds of crops (28 million kg of produced food [100], and a rate of 8% of waste production [100], although other literature references presents even bigger rates, what resulted in 2 thousand tons of food waste available for the biogas production;

iv. **biogas production from pruning biomass** considered the same parameters of MSW ones and the number of pruning wastes generated in 2014 was of 140 t/day of waste [31].

v. **biogas production from livestock wastes** estimation used the methane potential for each kind of animals breeding, to know: oxen (206 heads, [100]), poultry (148.590 heads [100]), and pigs (734 heads [100]). For calculating the methane flow, the following equation was used:

\[
Q_{CH4}\left(\frac{m^3}{h}\right) = \left[\left(\frac{d}{m}\right) \times (h \times tm \times bp \times bmc)\right]/msv
\]

Where:

- \(Q_{CH4}(m^3/h)=\) total methane flow in m³ per hour;
- \(d=\) number of days; 365 days considered, the specific values can be found in [110–113]
- \(m=\) month;
- \(h=\) total number of heads;
- \(tm=\) total manure;
- \(bp=\) biogas production;
- \(bmc=\) biogas methane concentration;
- \(msv=\) methane specific volume
Annex B- General model assumptions and growth rates for each Key Assumptions.

The city reference energy system for the BY used an extensive data compilation from local and national statistics, reports and others public data’s available on [31,33,34,36,49,64,65,67,70,101,102]. The compiled information was validated by cross-referencing additional official sources of information, such as [54,72].

The São Paulo city fuel composition and GHG and air pollutants emission data were uploaded into the software according to [103]. When it was not possible to get the city or Brazilian data, the Intergovernmental Panel on Climate Change (IPCC) emission factors were used. Nevertheless, this paper analysis focusses solely on GHG emissions. The growth rates of key assumptions are as follows:

- **Number of dwellings:** REF and BAU consider the expected number of inhabitants estimated for 2030 and a decline in the number of inhabitants per dwelling (from 3.2 to 2.8 persons per house by 2030 [77,104]). BET scenario assumes the improvement of energy service access of population share that lives in subnormal dwellings, this inclusion corresponds to the transfer of the subnormal dwellings number (398 thousand in 2014) into standard houses until 2030 (it was considered the 2008 occupancy rate of 4.02 people per subnormal dwelling [38]);

- **C&S area (m²):** REF and BAU considered a total growth of 5%\(^6\) (authors based on: [56]), as BET assumes a greater social insertion with better and more equal conditions on the access to C&S services, this is reflected in the expected per capita income growth of 1.95% per year for the period. This rate also took into consideration the percentage of people income that is spent on C&S services (around 30%), so the new total growth rate for the sector was 8.7% (authors based on [105,106]);

- **Industry GVA (R$):** REF and BAU considered that until 2030 the GVA growth rate is expected to be around 0.5% per year. (authors assumption based on [56]), and BET assumes a slightly higher GDP growth of 0.8% per year (authors assumption);

- **Number of PB:** REF assumed a low increase in the number of PB (8.5 thousand). Taking into consideration current statistics of the sector and the current political situation of the country, authors assumed that the public sector is not going to evolve more than in REF situation, so BAU and BET assumed REF grow rates;

- **Number of lamps/devices:** REF and BAU considered 97% coverage of the service (IBGE, 2010), with an annualized growth of 1.1%. Intended expansion of PL to 663 thousand lamps [85]. BET assumes a 100% coverage of the service within the study period, what corresponds to 2% annualized growth rate (authors based on data [35]);

- **Produced water (m³):** REF and BAU considered the expected increase of standard dwellings and the same service coverage of 77%. So, the total estimated amount of produced water in 2030 was of 5.2 thousand m³ (authors assumptions based on [56]). BET total estimated amount of 6.8 thousand m³ of produced water in 2030 corresponds to the municipality goal of sewage services universalization by 2024. It is in line with the goals of BET scenario on the assessment of the impact of the “informal city” urbanization. (authors assumption based on [32,85]);

- **Aggregate sector demand (GWh):** REF assumes a 0.8% per year electricity demand decreasing and 16% growth of NG per year (based on the analysis of historical series data from: [74]). BAU and BET are the same as REF;

- **Number of Transported Passengers:** REF and BAU considered only the influence of the population growth, and it was assumed an average increase of 0.6% per year in passenger’s transportation [31,56]. BET considered the 2.33 trips/day of city mobility rate (2014) [34], and 1.54 trips/day for the motorized travel (authors own assessment). The estimated future growth rate of 2.6% per year was considered taking in account: 1) the increase in the number of inhabitants, 2) the increase in the mobility index and 3) higher rates of economically active population. It aimed to double the 2014 index values to reach 3.1 and the economically active population rate of 6% (authors based on: [34,107–110], a lower rate than the

\(^6\) Growth rate was related to the expected growth of GVA for the sector in the period (2014-2030) for the city.
Number of Transported Passengers: REF assumed 4.4% per year growth rate, observed in 2014-2016, and for 2016-2030 it was adopted the sector’s growth projections of national projections for the passenger’s transportation: 1.7% per year [37, 78]. BAU and BET are the same as REF.
Annex C - Final Energy Consumption per energy carrier and sector and per scenario

Table 11 - Final Energy Consumption per energy carrier and sector and per scenario in PJ and % [24].

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<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Households</td>
<td>PJ %</td>
<td>PJ %</td>
<td>PJ %</td>
<td>PJ %</td>
<td>PJ %</td>
<td>PJ %</td>
<td>PJ %</td>
<td>PJ %</td>
</tr>
<tr>
<td>Electricity</td>
<td>40.9 73%</td>
<td>50.1 73%</td>
<td>66.5 54%</td>
<td>54.1 70%</td>
<td>107.4 63%</td>
<td>88.6 78%</td>
<td>44.6 63%</td>
<td>70.4 71%</td>
</tr>
<tr>
<td>NG</td>
<td>5.4 10%</td>
<td>6.6 10%</td>
<td>47.8 39%</td>
<td>14.6 19%</td>
<td>51.9 31%</td>
<td>15.9 14%</td>
<td>17.5 24%</td>
<td>19.0 19%</td>
</tr>
<tr>
<td>Kerosene</td>
<td>0.0 0%</td>
<td>0.0 0%</td>
<td>0.0 0%</td>
<td>0.0 0%</td>
<td>0.0 0%</td>
<td>0.0 0%</td>
<td>0.0 0%</td>
<td>0.0 0%</td>
</tr>
<tr>
<td>LPG</td>
<td>9.6 17%</td>
<td>11.8 17%</td>
<td>8.9 7%</td>
<td>7.8 10%</td>
<td>9.7 6%</td>
<td>8.5 8%</td>
<td>7.5 11%</td>
<td>8.5 9%</td>
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<td>0.1 0%</td>
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### Annex D - Final Energy Consumption per end-use and sector, and per scenario

**Table 12 - Final Energy Consumption per end-use and sector, and per scenario in PJ and % [24].**

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<td>-2.2%</td>
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<td>-4.1%</td>
<td>-4.0%</td>
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<tr>
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<td>n/a</td>
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<td>-3.6%</td>
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<td>n/a</td>
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<td>n/a</td>
<td>n/a</td>
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<td>Water Treatment</td>
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<td>n/a</td>
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<tr>
<td>PB</td>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>C</td>
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<td>n/a</td>
<td>n/a</td>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
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<td>n/a</td>
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</table>

Note: HR rates from analyses of [48.59–67]; C rates authors assumptions based on [74].