# The dawn of urban energy planning – synergies between energy and urban planning for São Paulo (Brazil) megacity

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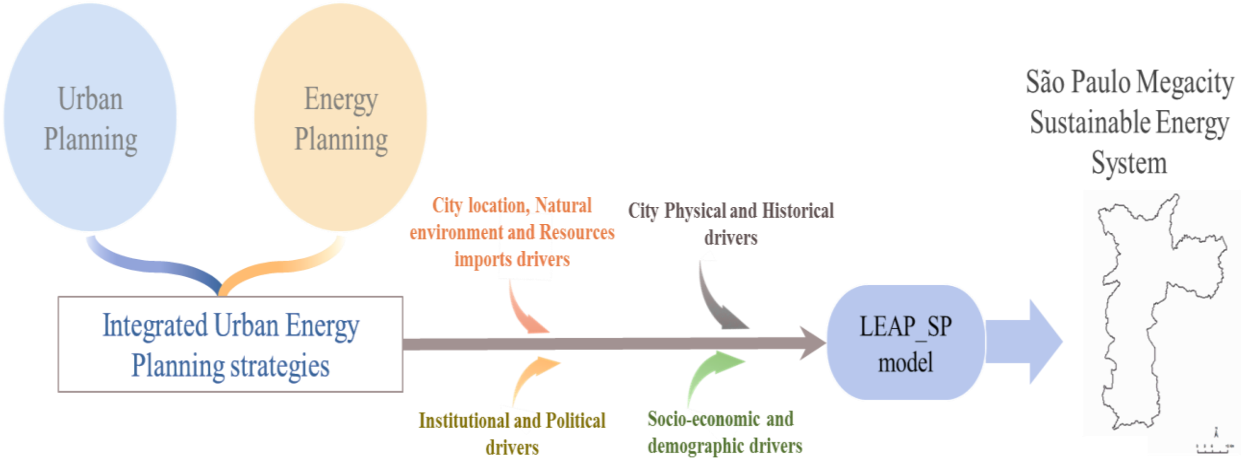
## GRAPHICAL ABSTRACT




## ABSTRACT

Energy use in cities has attracted significant research in recent years and city level energy planning is becoming a required task driven by the contribution of decentralized renewable electricity production and a demand-side approach towards greenhouse gases emissions reduction. However, traditional energy planning approaches are limited because they tend to focus on technology substitution. We argue that a more ambitious and holistic urban energy planning approach is desirable. This paper proposes a novel method to integrated Energy and Urban Planning solutions assessment by modeling and quantifying urban energy planning strategies impact in terms of energy savings, greenhouse gases emission reduction and in increasing cities renewable distributed and local energy generation. We apply the approach to São Paulo megacity using the LEAP_SP urban energy simulation model (from 2014-2030) through four scenarios. Results showed that by using a traditional energy planning approach, it is possible to reach 2% energy savings from the current situation, 18% greenhouse gas emission reduction and a three-fold increase in renewables deployment. When applying only urban planning strategies these benefits are of 10% energy savings, 8% greenhouse gas emission reduction and one-fold increase in renewables deployment. If a more holistic urban energy approach is adopted by integrating both energy and urban planning policies, gains increase to 12% energy savings, 30% greenhouse gases emission reductions, and a four-fold increase in renewable distributed and local electricity generation from the current city status.

**Highlights:**

- Integrated Urban Energy Planning Strategies for new and established cities;
- São Paulo city real data multisectoral Urban Energy System development;
- Assess the benefits of combining urban and energy planning strategies;
- Urban Energy Planning strategies integration creates substantial synergies;
- Major impact of urban energy planning strategies is for GHG emission reduction.

**Keywords:**

Urban Energy Planning; São Paulo Urban Energy System; Megacity; LEAP_SP simulation model;

**Glossary of terms and acronyms**

Air Transport- AT
Distributed Generation- DG
Energy Conservation- EC
Energy Efficiency- EE
Energy Planning- EP
Energy Policies strategies Scenario- SEP
Energy Sector- ES
Greenhouse gases- GHG
Historical Rates Scenario- SHR
Long-range energy alternative planning model- LEAP
Municipal Solid Waste- MSW
Natural Gas- NG
Photovoltaic- PV
Public buildings- PB
Public lighting- PL
Public transport- PT
Renewable energy sources- RES
Residual Fuel Oil- RFO
Trade and Services- T&D
Urban and Energy Policies strategies Scenario- SUEP
Urban Energy Planning- UEP
Urban Energy Systems- UES
Urban heat island- UHI
Urban Mobility- UM
Urban Planning- UP
Urban Policies strategies Scenario- SUP
Wastewater-treatment- WWT
Water Treatment- WT

# 1. Introduction

Cities are being encouraged to adopt carbon mitigation measures by promoting Energy Planning (EP) policies and actions. In this new endeavor, cities, their management and inhabitants, need to gain expertise and consider the urban energy system analysis and EP strategies in their Urban Planning (UP) process.

Urban energy needs, greenhouse gases (GHG) and air pollutants emissions have a strong relationship with cities' physical, social, economic and environmental aspects (Yazdanie et al., 2017). Decision-making and planning processes made today will have a long lasting impact, and will determine the boundary conditions for the future of Urban Energy Systems (UES) planning (Creutzig et al., 2016).

Recent literature on UES advokes that systemic characteristics of urban energy use are generally more important determinants of urban energy efficiency than those of individual consumers or of technological artifacts (Grubler et al., 2012). The latter is the traditional focus of end-use oriented energy efficiency policies (also known as demand-side approach).

Therefore, it is necessary to go further than this traditional focus. Recently, Creutzig et al. (2018), made a call for collaborative and transdisciplinary efforts in research to more holistically address demand-side solutions that effectively cope with climate change challenges. The authors refer the importance of going beyond efficient technology design and emphasize the relevance of influencing life-styles through UP.

Worldwide cities' ascension has increased the relevance of Urban Energy Planning (UEP) which highlights the interlinkage between UP and EP (Ruparathna et al., 2017). This is becoming a pressing issue in the international debate and scientific literature. However, both UP and EP knowledge areas refer to the difficulty of measuring the impact that each individual urban attribute or parameter[2] has in the city energy system.

According to Silva et al. (2017), this can be attributed to: i) the difficulty of isolating urban form and other urban parameters from the energy demand drivers; ii) the fact that there are many variables in cities to be considered and that the interaction degree among each of them is not yet fully defined and understood; iii) some urban attributes can have an antagonistic effect. For example, using building's rooftop for photovoltaic electricity production excludes its use for solar water heating or green roofs. Furthermore, investing in high-rise buildings for accommodating more persons or increasing green urban areas with high trees can also negatively impact solar irradiation that reaches solar panels. Finally, iv) there are not many empirically measured impacts regarding effects of urban energy strategies adoption at city level.

There is a broad set of urban parameters with relevance for energy conservation in UP (Torabi Moghadam et al., 2017), such as the urban form and the mobility sector. Nevertheless, existing research has been sectorial and focusing only on one or a few of these at a time (Naess, 2004; Rickwood et al., 2008). Moreover, the energy trade-offs

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[2] Further explained in the text in section 2.

between the different urban form parameters have not been properly explored (Silva et al., 2017).

The UES literature field mostly suggests demand-side solutions for buildings and transport sectors that rely on technological replacement, including building retrofit (G. Simoes et al., 2018), or solely on supply-side technology renewable energy sources (RES) development pathways (Adam et al., 2016; Amado and Poggi, 2014a). Even though there is a wide array of studies emphasizing the relation between urban systems and energy systems (Brownsword et al., 2005; Peng et al., 2015; Silva et al., 2017; Zheng et al., 2017), not all factors that influence this relation are simultaneously addressed, or fully quantified. It is not yet clearly understood to what extent and how UP affects the UES.

UEP can be defined as a combination/integration between two currently different and separated fields: the EP area and the UP practice. Such integration is pointed out as a target area to deal with a confluence of key problems and opportunities, mainly regarding climate change issues (Grubler et al., 2012). However, to effectively promote UEP it is necessary to review and improve established methods on modeling energy systems at the city context.

Considering the literature gaps pointed out, this paper proposes a novel integrated solutions matrix of energy and urban planning strategies aimed at modeling and quantifying UEP strategies impact in both the demand and supply side.

To do so, we address the following research questions: what types of solutions and strategies should be considered in a holistic manner to improve the sustainability of UES? To what extent UP and EP measures overlap? What are the synergies obtained by considering both energy and urban planning strategies when aiming for a more sustainable energy system?

To answer these questions, the proposed method aims to promote a more sustainable UES promoting energy savings and increased RES, leading to lower GHG and air pollutant emissions and to more local RES energy production. Twenty-nine UEP strategies were applied to a case study city (São Paulo megacity, Brazil) to assess the sustainability gains for the city’s energy system, regarding impact on energy savings, GHG emission reduction, RES use and local city energy generation by 2030. The Long-range Energy Alternatives Planning System (LEAP) energy simulation model (Heaps, 2006) was applied for modeling São Paulo’s UES in order to characterize the megacity current and future energy system.

Several scientific publications mention the importance of using modelling tools to analyze UES (Samsatli and Samsatli, 2018). There is an increased number of works that applies optimization energy models at the urban scale (Farzaneh et al., 2016; Gargiulo et al., 2017; Yazdanie et al., 2017). However, there is still a few studies using simulation models at city level, some of which making use of the LEAP model. Peng et al. (2015) used LEAP to study urban passenger transport and the amount of energy and emission reduction potential for Tianjin. Yang et al.(2017) and Zhang et al. (2011), analyzed the implication of low-carbon policies for cities in China (Ningbo and Beijing respectively), and Phdungsilp (2010) used the software to visualize the impact of low-carbon policies for the city of Bangkok in Thailand.

We take their work a step further in this paper by explicitly modelling both EP and UP strategies and for the whole urban system (all sectors and not only buildings or transport). This is innovative since existing literature mostly considers only EP. Examples of work considering only traditional EP for some specific end-uses are for city heat demand (Quiquerez et al., 2017); buildings heat demand (Mutani et al., 2016), and lighting energy consumption in buildings (Zheng et al., 2017). Other work have an even narrower focus, looking into a specific technology performance potential regarding energy savings, e.g. smart grids (Hati et al., 2017), net-zero energy buildings (Aksamija, 2015) or electric vehicles (HomChaudhuri et al., 2016). Alternatively, a smaller body of work focuses solely on UP measures separately as in Gunawardena et al. (2017) and Sharp et al. (2014).

Furthermore, the majority of scientific literature tends to focus on individual city economic sectors, e.g. transport (Costa et al., 2017) or buildings (Voulis et al., 2017; Yang et al., 2018). As stated, in this paper we take one step further by studying the separate and combined effect of each UP and EP measure. This aims to assess their synergies and impacts on the city's future final energy demand. Other authors considered this integrated approach, but only in a theoretical way (i.e., Leduc and Van Kann, 2013). The proposed holistic quantitative analysis here presented has never been done before for existing megacities.

This paper is structured as follows: besides this introduction section, the following section presents an overview of UES main drivers and interrelations, as well as a review of the UP parameters with energy relevance, followed by the presentation of the proposed integrated solutions matrix of energy and urban planning strategies. Section 3 presents the case study materials and methods for the application of the proposed UEP solution matrix to São Paulo megacity. Section 4 presents the results and discussion, and Section 5 concludes the paper, highlighting learned lessons, limitations and suggestions for future work.

## 2. Proposed Integrated Solutions Matrix of Energy and Urban Planning Strategies

This section presents a new integrated solutions matrix of energy and urban planning strategies to be considered while modeling UEP approaches. The matrix combines urban energy use drivers from literature with concrete parameters and strategies. The aspects of influence, interdependencies and/or linkages between UP and EP are identified.

### 2.1. Urban energy uses drivers

As previously mentioned, there is a lack of comprehensive information on all the urban energy uses drivers and their interrelations (Grubler, 2012; Grubler et al., 2012). Urban energy use drivers can be considered as the city aspects that most strongly affect how energy will be required and consumed. Each driver in turn can be impacted by a series of social, economic, natural or even engineering parameters. These represent all variables that characterize any urban city system (energy and non-energy related). We propose to structure the urban energy use drivers identified by Creutzig et al. (2018); Grubler (2012);

Grubler et al. (2012); Hendrickson et al. (2016); and Silva et al. (2017) into groups of parameters, as follows:

i) **City Physical and Historical drivers** that aggregate the following _parameters:_ *urban form* (including the built urban environment, transportation infrastructure and density), together with the city economic structure, the national and international *urban function and integration* (i.e., the role that different cities play in the national and global division of labor from production and consumption perspectives). These physical and historical aspects play an important role in determining the city energy consumption patterns and needs;

ii) **Socio-economic and demographic past, current and future development drivers** that have as main _parameters:_ *socio-economic city situation, human capital resources,* and the *behavior aspects* (i.e., culture, consumption patterns and lifestyles) that have strong influence on city energy consumption, plus the city *economic sectors* (households, trade and services, industry, etc.) that determine the city energy demand;

iii) **Institutional and Political drivers** that present as main _parameters_: *governance aspects* and city past and current laws, policies and programs, or, the city *policy instruments* that play an important role in the city energy usage, as well as in influencing people's behavior;

iv) **City Location, Natural Environment and Resources Imports drivers'** _parameters_ that include the *bioclimatic city aspects*, as well as the availability of *local resources* and the access to exogenous resources (or *import needs* considering that the city belongs to a bigger context, i.e. the region and country). These influence the city degree of energy dependence; the city energy needs and its impact boundary.

The interactions between these urban energy use drivers may change from city to city. Moreover, although they are different drivers, they are all interconnected and influence each other with strong feedbacks and synergies, as depicted in Figure 1. It presents the four **drivers** and their respective _main parameters_ relation and interlinkages, showing that acting in one parameter is going to influence more than one city driver at the same time. Moreover, as it is possible to see, all parameters are merged in the figure's central part highlighting the intrinsically holistic nature of UEP.

The drivers presented in Figure 1 are further explored in the next section that presents the Integrated Solutions Matrix of Energy and Urban Planning Strategies proposition for UEP approaches.

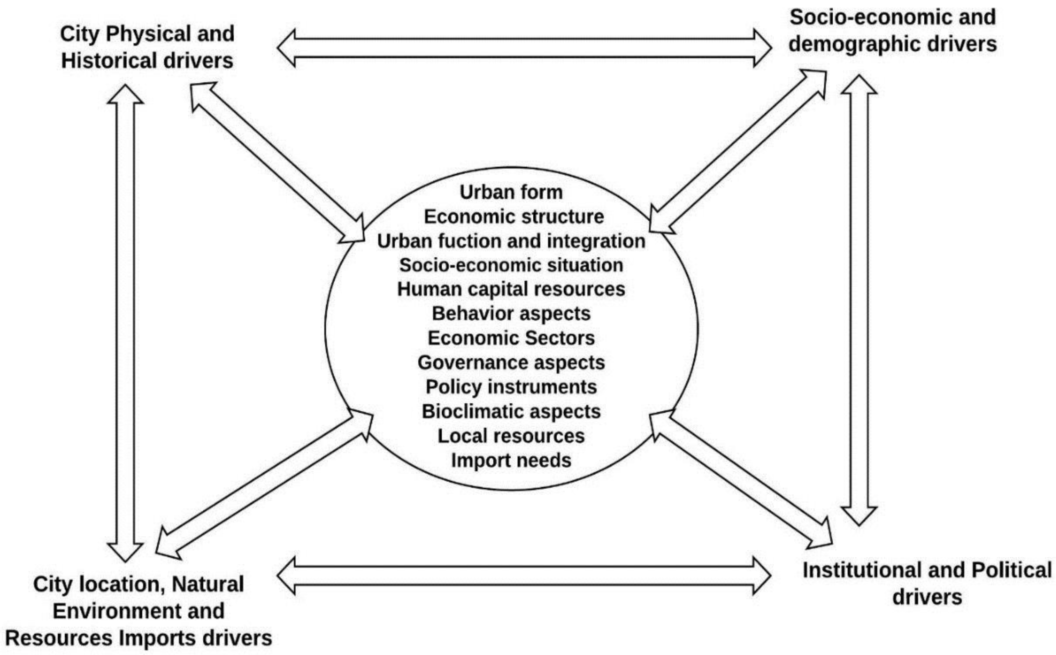


***Figure 1- Representation of the four urban energy use drivers and parameter's influence on each other***

## 2.2. Modelling the integrated solutions matrix of energy and urban planning strategies

The urban energy use drivers affect the city components and will determine the city's energy needs. Understanding the urban energy system and acting in UEP allows promoting energy savings and GHG emissions reduction through an integrated approach that should also ensure a better quality of life for the cities' inhabitants.

The UES is a complex web of interactions with countless causes and effects, which are articulated in the proposed integrated solutions matrix of energy and urban planning strategies for new and existing cities (Figure 2).

The proposed matrix (Figure 2) is structured along the four presented urban energy use drivers, its respective parameters, the aspect/services that the city delivers to its residents, the possible strategies to improve the city's performance, their influence area (i.e. thermal comfort, mobility index, resources needs and energy) and respective possible impacts.

In Figure 2 is possible to visualize the identified urban energy use ***drivers'*** connections and each respective <u>*parameters*</u> with the correspondent city services. These services that the city should provide include housing, mobility, job provision, education, healthcare, food & water provision, leisure and security. In turn, supplying these city services is affected by: (i) the *city infrastructure* (i.e. built environment, city density, transport infrastructure and other support infrastructure for energy supply, waste, water and wastewater collection and treatment) and (ii) the city available resources, or the *city* *resources* (i.e. water, food, energy and waste commodities that can be imported or locally produced).

The numbers in each strategy indicate that they are influenced by the corresponding aspect/services (e.g. buildings density is determined by city density, built environment, mobility infrastructure and city services). The star symbol identifies the strategies modelled for the São Paulo case-study (further detailed in this section). These strategies were selected based on literature review, as well as on the analysis of the current and standard normative multilevel governmental international and Brazilian Urban and Energy Planning Policies and Plans.

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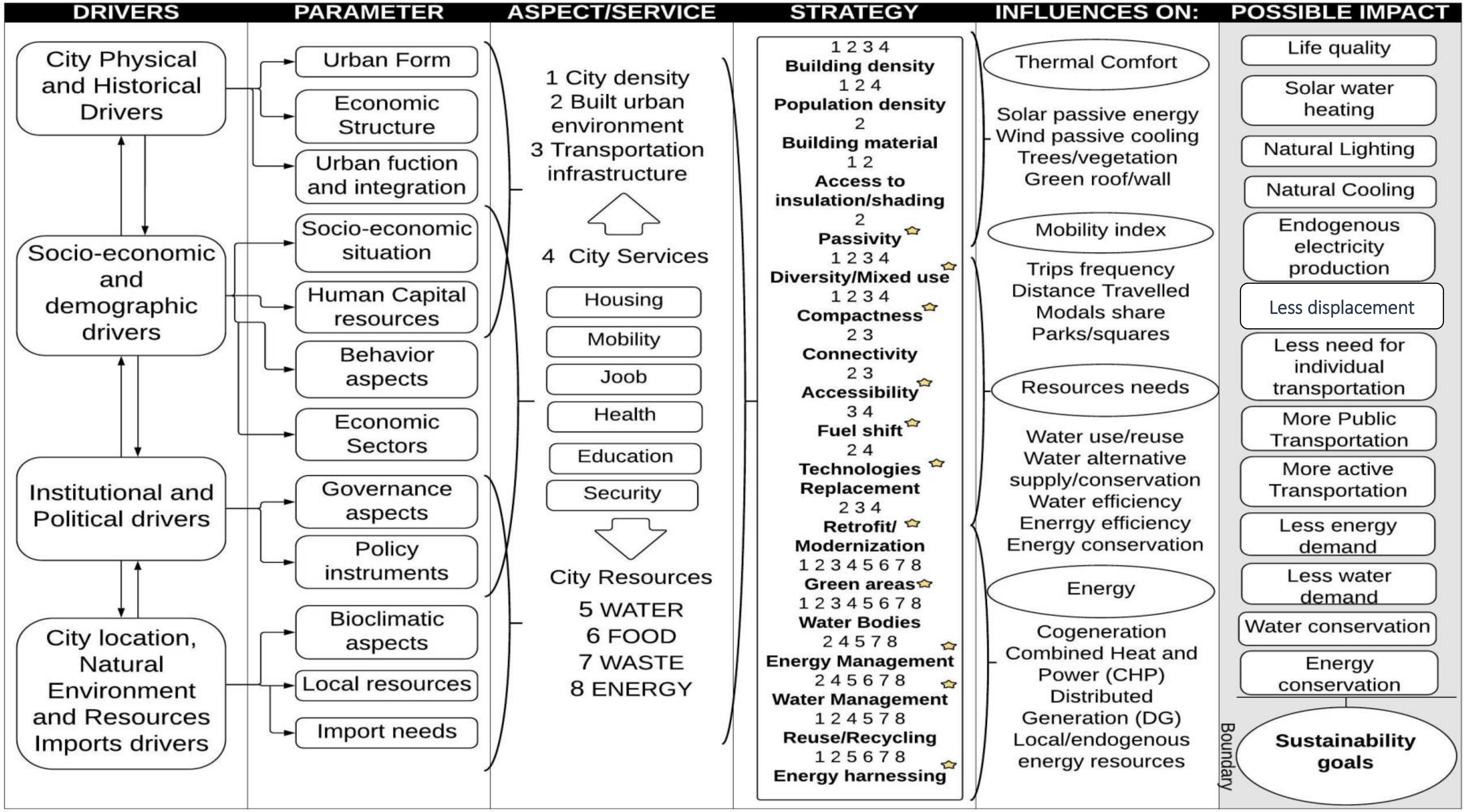


***Figure 2- Integrated Solutions Matrix of Energy and Urban Planning Strategies for new and established cities.***

By considering the full list of Drivers, Parameters, City Services/Infrastructure/Resources and their interlinkages, it is possible to identify a comprehensive and holistic list of strategies for promoting more sustainable UEP (via energy conservation (EC), energy efficiency (EE) and more RES inclusion). In this paper EC refers to any behavior, strategy or policy that reduces or avoids energy needs resulting in less energy use, such as walking instead of driving. EE refers to maintaining the same level of energy service while using less energy to do so, for example by driving a more efficient car (Institution of Mechanical Engineers, 2009).

The implementation of the matrix for UEP modelling (Figure 2) is presented in Table 1. The considered urban and energy drivers, their respective parameters and corresponding urban and/or energy planning strategies are presented followed by their respective aspects of influence, as well as the interdependencies and/or linkages between UP and EP. The table also includes the possible solutions and impacts to be modelled as UEP synergies and the city sectors for which they can be simulated.

***Table 1- Implementation of the proposed integrated solutions matrix of energy and urban planning strategies for UEP modeling***

| **Urban energy use Drivers** | **Parameter and Strategy** | **Aspects of Influence, interdependencies and/or linkages between UP and EP** | **Possible Strategy to be simulated/ modelled** | **Sectors in which the Strategy can be simulated** |
|---|---|---|---|---|
| Socio-economic and demographic drivers | Behavior aspects- *Energy Management (EM)* | Education actions and EM practices can help individuals to make better choices in the subject, what can lead to a bigger awareness and better energy use, resulting in energy consumption reductions= energy and economy savings. | *Industry Energy Management*: with 10-30% range of reduction in electricity demand (EPE/ MME, 2007; Geller et al., 2004; Schulze et al., 2016)<br>*Buildings Energy Management*: with 5-20% range of reduction in electricity demand (Lee and Cheng, 2016; Savage, 2009)<br>*Water Treatment Sector Energy Management* – with 10-25% range of electricity reduction demand (EPE / MME), 2016a, 2007; MME, 2011) | All sectors |
| | Economic Sectors- *Combined Heat and Power (CHP)* | The Residual Heat from the industry processes can be used to generate electricity for self-consumption, or for the grid, as well as, to invest in a hot/cold water distribution. This implies gains of EC and EE. | *Industry CHP:* according to (IEA, 2017) can reach 10-20% energy savings. | Industry |
| City location, Natural Environment and Resources Imports drivers | Local Resources- *Green areas* | Integration of green and free areas in the city assists in the microclimate maintenance and permeability leading to gains in EC for the surrounding areas, as well as it helps to reduce the effects of Urban Heat Islands (UHI). | *New Green Areas Implementation:* from10% up to 60% of energy savings for cooling end use (Shashua-Bar and Hoffman, 2000; Zhang et al., 2014). The size and the distances between the green areas also impact these results.<br>*Green Roof Top/Wall:* the range of energy saving regarding the cooling effect is from 4%-40% (Kikegawa et al., 2006) | Buildings |

| **Urban energy use Drivers** | **Parameter and Strategy** | **Aspects of Influence, interdependencies and/or linkages between UP and EP** | **Possible Strategy to be simulated/ modelled** | **Sectors in which the Strategy can be simulated** |
|---|---|---|---|---|
| | Local Resources- *Water Management* | Water is a fundamental resource in a city. Water bodies can act as security reserves, as local climate maintenance agents, for sports venues among other multiple water uses. Energy and the water use are closely linked. Energy is needed in the water city distribution as well as for its treatment and so on. | *Water Management*: electricity savings due to the reduction of water demand in buildings sector (kW h/year) can be calculated as an equation of the potential for potable water savings in buildings sector (m3/year) times the electricity consumption per m3 of water produced (kW h/m3) (Proença et al., 2011). With the city reference data of energy consumed per produced water, it is possible to get a percentage of energy saving. | Buildings |
| | Local Resources- *Water Bodies* | | *Water Bodies:* can have a similar impact on the energy saving results of green areas for cooling proposes. Nevertheless, for better accuracy it could be necessary to calculate the local Degree Days and the Thermal Comfort Temperature (for details see: Ewing, 2010; Kohler et al., 2017). ps. the same method can be used for green areas | |
| | Local Resources- *Distributed Generation* | Increase Local and Renewable energy generation inside the city can help cities to be less susceptible to grid blackouts as well as to be more self-sufficient. Main local energy resources are solar, wind and hydro sources. | *PV and Wind potential:* needs to be calculated for the city context. Information about methodology on how to do it at the city scale is available in: Adam et al., 2016; Amado and Poggi, 2014b; Kanters et al., 2014; Mann et al., 2006; Robinson, 2006; Theodoridou et al., 2012. | Buildings or free areas in the city |
| City Physical and Historical drivers | Urban Form- *Population and Buildings Density* | Although scientific literature is divided about density positive and negative impacts on UEP strategies for energy savings[3], it is expected that a bigger density influences positively travel patterns because it potentially brings urban activities closer, | *Public Transportation and Non-motorized transportation*: savings of 0.5 kWh per passenger per day when collective/public and non-motorized transport is used instead of private cars. Consumption of fuels per passenger and the emission volume per passenger of public transport is about 40% lower (Carvalho, 2011; Marins, 2014). | Urban Mobility (UM) |

[3] According to Mafalda et al. (2017), density can be classified as a driver of lower energy intensities or as a proxy for other variables of dense urban areas, such as proximity to public transportation or accessibility to activities (Ewing et al. 2008; Ewing and Cervero 2010). Density criticism usually points it's as a cause of traffic congestion, crowding and lower housing availability (Echenique et al., 2012), thus increasing energy needs, air pollution and noise (Gordon and Richardson 1997; Nijkamp and Rienstra 1996). In addition, while density may decrease everyday travel needs, it has been linked to higher levels of out-of-city leisure travel by plane (Holden and Norland 2005).

| **Urban energy use Drivers** | **Parameter and Strategy** | **Aspects of Influence, interdependencies and/or linkages between UP and EP** | **Possible Strategy to be simulated/ modelled** | **Sectors in which the Strategy can be simulated** |
|---|---|---|---|---|
| | | plus denser urban areas also enable and promote more reliable public transport. | | |
| | Urban Form- *Mixed Use and Compactness* | Encourage the Mixed Use and the city Compactness (or the establishment of multi-city centers, with good provision of housing, work and services) can lead to gains in EE and EC because a closer proximity between services commerce and housing can result in less need for travel to access the different services of the city. Also, can act as an encouragement for transitions from motorized travels modals to non-motorized ones. | *Non-motorized or Active mobility*: as it demands only human energy for locomotion, it implies in EC gains, and the reduction of GHG emissions and pollutants. The range of energy saving is equivalent to the range of the change from motorized to non-motorized modal. The range can be determined to take into consideration the share of the population that is eligible to the active mobility, inside this group, the share of people that travel less than 5 km to reach their destination among other socioeconomic factors that should be locally considered | UM |
| | Urban Form- *Passivity, Retrofit and Modernization* | Passive Architecture Investments can result in more efficient buildings that can provide the same energy service with a lower energy need for lighting and thermal comfort. In Buildings it is also possible to invest in Distributed Generation (DG) using solar panels to heat water or to generate electricity. | *Natural Lighting:* The range of energy saving varies from 30 to 50% of energy savings (Aboulnaga, 2006).<br>*Solar water heating and Solar Photovoltaic:* depending on the built environmental attributes, some passive solar building could accomplish near net zero energy buildings (Aelenei and Gonçalves, 2014).<br>*Passive Colling (shading and wind):* around, at least, 20% of energy saving (Taleb, 2014). | Buildings |
| | Connectivity- *Public Transportation* | Ensure good connection with Public Transportation network can encourage public/collective transport, that by your turn, leads to gains in EE and a decrease in the GHG emission. | *Public Transportation and Non-motorized transportation*: savings of 0.5 kWh per passenger per day when collective/public and non-motorized transport is used instead of private cars. Consumption of fuels per passenger and the emission volume per passenger of public transport is about 40% lower (Carvalho, 2011; Marins, 2014). | UM |
| | Accessibility- *Non-motorized transportation* | Investment and construction of non-motorized transportation infrastructure increase the incentive to exchange modes of transport, this could lead to gains in EE and a decrease in the GHG emission. | | |

| **Urban energy use Drivers** | **Parameter and Strategy** | **Aspects of Influence, interdependencies and/or linkages between UP and EP** | **Possible Strategy to be simulated/ modelled** | **Sectors in which the Strategy can be simulated** |
|---|---|---|---|---|
| | Fuel shift- *Private Transportation* | Investments in renewal of the vehicle fleet, for more efficient and fewer fossil vehicles can lead to gains in EE and a decrease in the GHG emission. | *Fuel shift:* increasing the participation of private transportation that uses ethanol and electricity as a fuel can reach zero GHG and Pollutants emission | UM |
| Institutional and Political | Policy Instruments- *Technological replacement* | Electrical appliances replacement inside buildings, generally, when considering similar devices, leads to EE gains, i.e., the same service will be provided with a lower energy intensity when old devices are replaced by new ones. | *Modernization and Technological Replacement:* can be simulated with a broad range of around 20%-60% of energy savings (Goldemberg, 2010). Exact number of savings requires an equipment ownership survey. | All sectors |
| | Policy Instruments AND Economic Sectors -*Energy harnessing* | Using Municipal Solid Waste (MSW), Water Waste Treatment (WWT) and other kinds of urban wastes, can enable the self-production of electricity (and a decreasing in electricity import grid). Also, cogeneration can lead to gains in EC and in the increase of the city installed capacity. | *Cogeneration WWT*: a range around of 40% of energy savings can be used to simulate the impact of the adoption of such a measure (IEA, 2017), although it is indicated that the biogas potential for electricity generation should be calculated.<br>*Urban Biogas production:* the energy potential needs to be calculated taking into consideration the sewage production and the urban solid waste production. | Waste Sectors (Water and Urban Solid Waste) and Industry |
| | Policy Instruments- *Reuse and Recycle* | Reuse and Recycling are activities that can act in EC. | *Reuse and Recycling*: the range of energy saving depends on the type of recycled material (see Colling et al., 2016). it is possible to calculate average energy savings if data on city waste composition is available. | Urban Solid Waste |

The 11 strategies identified with the star symbol in Figure 2 were used in this paper's case study, and are briefly summarized as follows:

- **Energy Management**: educational practices and awareness, incentives to minimize electricity inefficiency; EC practices; energy use monitoring and energy management plans' implementation; energy management software's use, and devices replacement;
- **Mixed use of urban land and Building Density or Compactness**: urban land mixed use (or diversity) is claimed to decrease motorized transport needs by shortening travel distances and bringing housing and urban activities closer (Baran et al., 2008; Jabareen, 2006; Marins and Roméro, 2013). They can also potentially create more thriving and interesting urban environments, which foster adoption of active modes as walking and cycling (Ewing, 2010; Ewing and Cervero, 2001; Silva et al., 2017). Compactness of the urban tissue refers to how clustered the built structures are (Ewing and Rong, 2008). Buildings' geometry affects buildings energy needs and can be seen as a pattern of city development (i.e. if the city has a disperse land-use pattern or if it is more compact);
- **Green Areas**: or green infrastructures may influence energy demand in different ways, i.e., urban parks and trees can help to maintain temperature and in decreasing the impact of the urban heat island (UHI) (Gago et al., 2013; Wong and Yu, 2005) which can result in lower cooling needs (Vaz Monteiro et al., 2016). The physical characteristics of green areas are also relevant to determine their impact on urban climate, i.e. their size, width, geometry and type of vegetation cover (Chun and Guldmann, 2014);
- **Retrofit, Modernization and Passive Architecture:** retrofitting old buildings can enable passive architecture investments that result in more energy efficient buildings capable to provide the same energy service with lower final energy need for lighting and thermal comfort. It is also possible to invest in distributed generation (DG) options in buildings using solar panels to heat water or to generate electricity. Finally, one other important EP strategy (not applicable to buildings) is the retrofitting of old power plants prolonging its lifetime and/or increasing its installed capacity;
- **Water management strategies**: there are several strategies to reduce water demand and thus act in energy savings associated to water treatment and distribution (Lam et al., 2017): i) efficiency improvement in water use (through the replacement of conventional equipment, i.e. flushing and tap pressure) and in the water distribution, i.e., reducing water losses in the distribution network; ii) reusing greywater for supplying the demand of non- potable water; and iii) using rainwater in cases where there is demand for non- potable water. This allows a reduction of wastewater-treatment (WWT) volumes due to rainwater harvesting and greywater reuse for landscape irrigation and other outdoor uses, leading to energy savings;
- **Waste Reuse, Recycling and Reusing materials**: there are different ranges of energy savings for each kind of recycled and reused material which are city

specific. Furthermore, if waste production is minimized, the waste volumes to collect and treat are also reduced, resulting in energy savings;

- **Technologies Replacement**: this refers to the replacement of electrical appliances (and other equipment) with more efficient ones, as well as replacing energy technologies with other ones operated with a different fuel to improve EE (e.g. using natural gas for cooking instead of wood or using electricity for mobility instead of diesel or gasoline);
- **Connectivity and Accessibility**: greater connectivity shortens distances to be traveled and potentially leads to reduced energy demand (although this effect is not consensual). It also may encourage walking and other active mobility modes, making urban areas more accessible for walking and cycling. Connectivity is largely influenced by the spatial configuration of the urban network and is a widely acknowledged urban feature influencing travel patterns. Although accessibility has no single definition (Silva et al., 2017), it can be translated as the easiest way of reaching the desired destination (Geurs and Ritsema van Eck, 2001; Levine and Garb, 2002). The implications on energy demand will depend on the considered transport mode. Pedestrian and public transport (PT) oriented accessibility should thus be increased for achieving more EE transportation and reducing energy needs.
- **Fuel Shift:** changes in the share of fossil fuels by replacing them with renewables and by adopting new technologies (e.g. transition from fossil fuel cars to electric and hybrids cars) are popular actions that municipalities are supporting as a response to the climate change call for local action.
- **Energy Harnessing and Local Resources**: local energy resources potential (e.g. solar, wind, hydro, biomass) should be measured for determining and incentivizing electricity and water heating production potential within the city (among other energy services) (Leduc and Van Kann, 2013). Other forms of urban energy harnessing include generating electricity and/or heat with biogas from city's WWT, from municipal solid waste (MSW), and garden waste treatment or from residual process heat from industry. Furthermore, residual process heat can be used for space or water heating of nearby buildings by investing in hot/cold water distribution grid. This can be encouraged through UP strategies such as zoning that fosters close and mixed uses of urban land and makes using waste heat feasible.

## 3. Material and methods for modelling the integrated solutions matrix

In this section we describe how we have modelled the proposed integrated solutions matrix for the case-study of São Paulo megacity using the LEAP_SP simulation model for the period 2014-2030. The city boundaries were defined as the administrative region of São Paulo city (Figure 3). The macro metropolitan region of São Paulo was excluded from the analysis. Thus, we do not take into consideration the embodied city energy imports and exports.

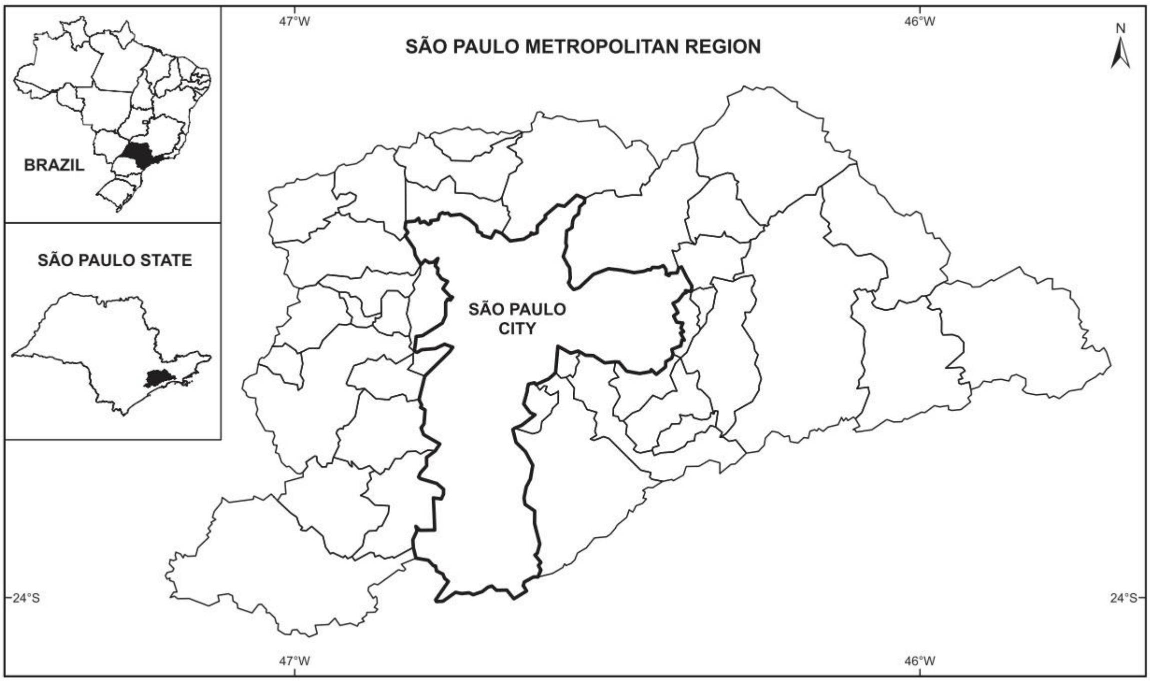


***Figure 3- Metropolitan region of São Paulo city and the case study area: city of São Paulo (Brazilian Ministry of the Environment, 2013)***

The case study considers the useful energy demand in all the city's economic sectors. The historic energy resources consumption evolution (from 2007-2017) in the megacity was considered to estimate each end-use and energy carrier's future demand. Losses for São Paulo's electricity distribution system correspond to city's electricity distribution company losses rate of 18%. Non-commercial energy was not included in the analysis.

## 3.1. LEAP_SP model

LEAP is a widely used energy-economy model, both for simulation and optimization, that builds energy scenarios using integrated planning and bottom-up data. The model uses energy demand and primary energy transformation data for the energy supply sector (transmission and distribution, primary energy conversion and energy resource extraction data). LEAP covers resources across all sectors of the economy (Heaps, 2006).

The LEAP_SP model is used to estimate GHG emission from energy use and production, emissions of local and regional air pollutants and short-term pollutants. The LEAP model also allows to analyze the impacts of adopting different energy policies on GHG emissions, energy savings and on reduction of local air pollution (Heaps, 2006). More information on LEAP can be found in Heaps, (2016) and Bhattacharyya and Timilsina, (2010).

The LEAP_SP model's main exogenous inputs are: (1) energy services and energy end-use for nine economic sectors (aspects regarding materials and types of construction were not included); (2) characteristics of existing and future energy-related technologies, such as efficiency and availability; (3) present and future sources of primary energy supply (solar photovoltaic (PV) and rooftop PV, imports of NG, micro-hydro, biomass from pruning, MSW, city livestock, urban agriculture and WWT sewage and cogeneration potential) and the corresponding techno-economic future potential; (4) final energy imports into the city (electricity, diesel, gasoline, ethanol, residual fuel oil or RFO and kerosene) and (5) policy constraints and assumptions.

Figure 4 presents the LEAP_SP model overview with the main model macro assumptions that influence directly energy demand and supply scenarios evolution. The model premises and assumptions were determined according to literature review on urban and energy planning issues. It also considers data collection on current and future energy technologies, energy efficiency and all relevant energy balance information for the city in the base-year (BY)[4].

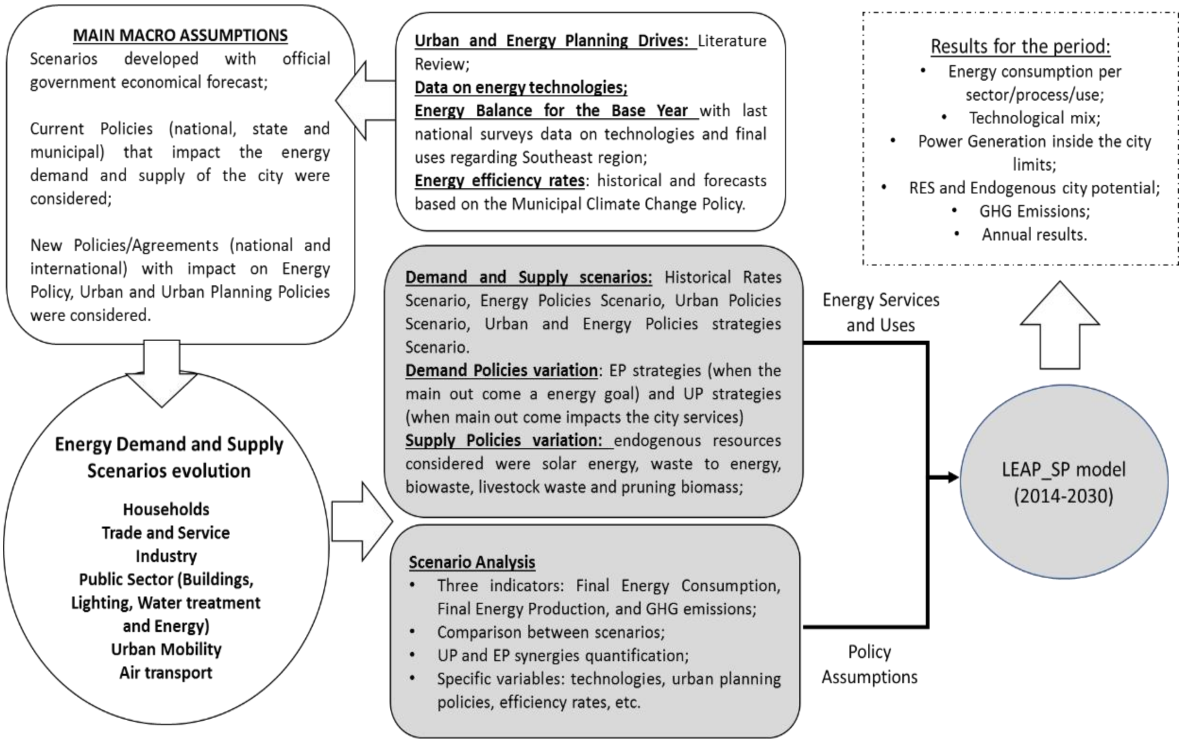


***Figure 4- LEAP_SP model overview***

Annex E presents the economic sectors, subsectors, services, end-uses technologies, energy resources and carriers considered in LEAP_SP. It includes three basic modules: energy supply, energy transformation and end-use energy demand (see Annex A and B), and nine end-use demand economic sectors: i) Households; ii) Trade and Services (T&S); iii) Industry; iv) Public buildings (PB); v) Public lighting (PL); vi) Water Treatment

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[4] Further in this section, information about the construction of each scenario referend in Figure 4 is going to be presented and explained.

(WT), vii) Energy Sector[5] (ES), viii) Urban Mobility (UM) sector, and; ix) Air Transportation (AT).

### 3.2. Model inputs on emissions data

LEAP_SP considers the following direct GHG and air pollutant emissions from energy use and production within the city: Particulate Matter (PM), Carbon Monoxide (CO), Non-methane volatile organic compound (NMVOC), Sulphur Dioxide ($SO_2$), Aldehydes, Nitrous Oxide ($N_2O$), Carbon Dioxide ($CO_2$) and Methane ($CH_4$). This means that the model does not consider the carbon emissions of products imported into the city, except for electricity.

Data on São Paulo fuel composition, GHG and air pollutants emissions were input into the model according to the state' environmental company information's (CETESB, 2015). When it was not possible to obtain city-specific or Brazilian data, IPCC emission factors were used. In any case this paper focusses solely on GHG emissions.

As this study uses the city's spatial scale, it was necessary to consider the energy imports from the country into the city. Thus, the assumed national electricity GHG emission factor (0.11 $tCO_2$/MWh) was the annual average emission factor calculated from 2013 until 2017 (MCTIC, 2018), that was kept constant till 2030. This emission factor was applied to the city's final emission results for each scenario to include the GHG emissions associated with electricity imports into the megacity.

### 3.3. São Paulo megacity case study

São Paulo has 12 million inhabitants[6](IBGE, 2017), a very high urbanization rate of 99.1% (Brasil, 2010), and hosts 5.9% of the country's population. It is the largest city in Brazil, the sixth most populous city in the world, and the 3rd largest urban conglomerate in the globe (Habitat, 2015). The megacity contributed in 2011 with almost 12% of the national GDP and has the largest industry park in the country.

The city has around 486 million $m^2$ of built environment regarding residential, commercial, industry, health, education and cultural urban land used. It has a vegetation cover of around 676 million $m^2$ (Info cidade, 2015) and produces an average of 28 million kg of food per year (urban agriculture) (CATI/IEA, 2009).

Regarding sewage and MSW production, São Paulo produces 6.300 t/day of organic waste, 30 thousand tons of electronic waste, 104 million $m^3$/year of sewage and 805t/day of sewage sludge (REDE NOSSA SÃO PAULO, 2014).

The São Paulo city had in 2014 an electricity generation installed capacity within the city limits of 899 MW (Agência Nacional de Energia Elétrica - Aneel, 2017). Table 12 (Annex D) presents the electricity generation installed capacity located inside the city limits per type of power plant, number of units, total installed capacity (kW) and age.

To estimate the city's local RES potential for electricity generation the following energy

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[5] Energy Sector regards the internal consumption of electricity for the activities of transmission and distribution and natural gas for co-generation.

[6] In the BY it was 11,5 million inhabitants.

resources possibilities were considered: i) solar rooftop photovoltaic potential; ii) biogas from city livestock, pruning from parks and other green areas, MSW treatment, urban agriculture biomass waste, and WWT sewage and cogeneration potential. More details on materials and assumptions are available in the annex C.

### 3.4. Modelled scenarios

To analyze São Paulo UEP potential using LEAP_SP four scenarios were developed:

i) Historical Rates Scenario (SHR),
ii) Energy Policies strategies Scenario (SEP),
iii) Urban Policies strategies Scenario (SUP);
iv) Urban and Energy Policies strategies Scenario (SUEP).

SHR scenario is the business as usual scenario that considers i) ongoing urban and energy city policies, and ii) adoption of the historically observed rates of energy consumption and supply in the city in the period 2007-2016 according to the city and São Paulo state annual reports. The city energy demand was identified for each sector and energy carrier and translated into annualized rates, reproduced throughout the modelled period (2014-2030).

SEP and SUP scenarios adopt the same growth rates than SHR, but in those scenarios additional groups of Urban and of Energy policies strategies were simulated in each, respectively. Finally, SUEP is the scenario that combines SUP and SEP policies strategies and aims to quantify the synergies obtained by integrating both UP and EP strategies.

Table 2 presents all modelled strategies and solutions of the proposed integrated matrix for the four scenarios. It also presents the sectors on which the scenarios were simulated, and the main expected steering and co-benefit effects. Details on the modelling of each strategy are presented in the Annex C.

Steering effects of the modelled strategies refer to the main desired expected outcome from its implementation (see Simoes et al., 2015). The steering effect was used to allocate the modelled strategies as UP or EP strategies. Thus, if the strategy has as main desired steering effect achieving an energy goal (energy saving, GHG emission reduction, or reducing the energy bill) it was considered EP, even if was a strategy usually developed by UP practitioners (i.e. all building passivity strategies are related to the UP and urbanism attributes). This is also the case of the following UP selected strategies: natural lighting, solar water heating, solar PV, and industry CHP.

***Table 2- Considered urban and energy policies strategies in the modelled scenarios***

| # | Simulated/ modelled Solutions | SEP | SUP | Simulated Sectors | Main steering effect | Main Co-effects |
|---|---|---|---|---|---|---|
| 1 | No usage of Lighting Kerosene | | ✓ | Household | Improve quality of lighting energy service | Reduce health risks |
| 2 | More Efficient Refrigeration | ✓ | | | Save energy: EE | Reduce energy bill |
| 3 | More Solar Water Heating [1] | ✓ | | | Reduce dependence on exogenous energy imports, save energy (EC) and reduce GHG emissions | Reduce energy bill and the peak load |
| 4 | More LED- Lighting | ✓ | | Households; T&S; PB and WT | Save energy: EE | Reduce energy bill |
| 5 | More Efficient air conditioning | ✓ | | Households; T&D; PB | Save energy: EE | Reduce energy bill |
| 6 | Buildings Energy Management | ✓ | | | Save energy: EC | |
| 7 | More Natural Lighting | ✓ | | | | Reduce energy bill, improved well-being of building users |
| 8 | Water Reuse of greywater and tec. replacement (dual flush) | | ✓ | Households; T&S and WT | Save water | Reduce energy, reduce water and energy bill |
| 9 | New Green Areas- from 100 parks to 167 parks | | ✓ | Household; T&D | Improve quality of life of citizens | Improve health, lower criminality and reduce energy consumption (among other) |
| 10 | More Efficient water pumps | ✓ | | T&D; PB; WT | Save energy: EE | Reduce energy bill |
| 11 | Public Lighting with LED | ✓ | | PL | Save energy: EE | Reduce energy bill |
| 12 | Industry Co-generation | ✓ | | Industry | Save energy: EE | Reduce energy bill, increase competitiveness |
| 13 | Industrial Energy Management | ✓ | | | Save energy: EC | |
| 14 | Water Treatment Energy Management | ✓ | | WT | Save energy: EC | Save energy and Reduce energy bill |
| 15 | No fossil fuels on Public Transportation (PT) | ✓ | | UM | Lower GHG emissions | Save energy: EE |

| # | Simulated/ modelled Solutions | SEP | SUP | Simulated Sectors | Main steering effect | Main Co-effects |
|---|---|---|---|---|---|---|
| 16 | More Electric Cars- all taxis | | ✓ | | Improve air quality and public health and reduce GHG emissions | Save energy, reduce energy bill reduce, dependence on exogenous imports of fuels |
| 17 | More Public Transportation- as targets Plano Mob | | ✓ | | Improve air quality and public health, reduce GHG emissions and traffic jam | Save energy, reduce energy bill, allowing public transportation (demand x supply) |
| 18 | More Cycling- as targets Plano Mob | | ✓ | | | |
| 19 | Non-motorized or Active mobility- accessibility impact | | ✓ | | Improve mobility flows within the city and improve air quality | Save energy, lower GHG emissions and improve health |
| 20 | Non-motorized or Active mobility- mix use impact | | ✓ | | | |
| 21 | Fewer Losses- energy system | ✓ | | Transmission and Distribution (T&D) | Save energy: EE | Reduce energy bill |
| 22 | Retrofit Old powerplants | ✓ | | Supply Side | Ensure security energy supply and money economy in new infrastructure | Reduce energy bill |
| 23 | More PV- 16.5% rooftops T&D and Household | ✓ | | | Reduce dependence on exogenous energy imports, save energy and reduce GHG emissions | Reduce energy bill and the peak load |
| 24 | Electricity from MSW- biodigester | | ✓ | | Reduce MSW flows in the city, reduce dependence on exogenous energy imports | Save energy and reduce GHG emissions |
| 25 | Electricity from sewage sludge- biodigester | | ✓ | | | |
| 26 | Electricity from pruning waste | | ✓ | | Reduce MSW flows in the city | Save energy and reduce GHG emissions |
| 27 | Electricity from urban agriculture biomass waste | | ✓ | | | |
| 28 | Electricity from livestock wastes | | ✓ | | | |
| 29 | Electricity from WWT | ✓ | | | Reduce energy bill | Increase revenue by selling electricity and lower GHG emissions |

Many methodological adaptations were made since the current models do not yet connect or even understand all the interlinkages between urban policies and energy drivers. Therefore, the modeler must play this role, identifying what is influencing and impacting what, and deciding how to input this information in a language acceptable by the modelling tool.

Regarding the simulation modelling limitations, some economic sectors included in our proposed integrated matrix are not targeted by any of the strategies simulated in LEAP_SP. This is the case of the air transportation (AT) and energy sector (ES). Likewise, there are no strategies for all end-uses and technologies (i.e. cooking and vertical transportation; motorcycle, trains and subways). This was due to the lack of data for São Paulo for these sectors and end-uses, which hinders a meaningful simulation.

All scenarios translate current urban and energy policies, as well as the population's socioeconomic situation. Its future evolution follows official urban demand projections considering: a) population growth[7], b) number of dwellings, c) total municipal GDP[8] d) per capita income growth, e) current policies goals for the provision of energy services in the city (Table 3), and f) other assumptions for each sector, namely: evolution of PL, PB area, industry gross valued added (GVA) (see Table 3).

[7] The official projection for the population growth is from 11.51 million people in 2014 to 12.26 million people in 2030 (an average rate of 0.72% per year until 2020 and 0.47% per year until 2030 (F. SEADE, 2017).

[8] Official projection for 2030 is from 628 million R$ in 2014 to 680 million R$ in 2030 (F. SEADE, 2017).

*Table 3- Scenarios Key Assumptions and main data sources*

| Selected KA | BY information/data | Scenarios evolution information (2014-2030) |
|---|---|---|
| **Households sector-** # of dwellings | 3.57 million dwellings (F. SEADE, 2017). | a) 3.2 to 2.8 persons per dwelling in 2030 (EPE /MME, 2017a, 2017b);<br>b) 11.5 inhabitant to 12.3 in 2030 (F. SEADE, 2017);<br>c) estimated 4.37 million dwellings. |
| **T&S sector-** T&S area ($m^2$) | 105 million $m^2$ (SMDU and Deinfo, 2014). | a) expected a total growth of 5% (authors based on: F. SEADE, 2017)<br>b) estimated 110 million $m^2$ |
| **Industry Sector-** industry GVA (R$) | 66.8 million R$ (F. SEADE, 2017) | a) until 2030 the GDP growth rate is expected to be around 0.5% per year;<br>b) estimated 72.4 million R$ |
| **Public Sector-** # public buildings | 8.45 thousand buildings (SEESP, 2015) | a) assumed a low increase in the number of PB (8.5 thousand); |
| **Public lighting**- # lamps/devices | 560 thousand lamps (PMSP, 2017) | a) 97% coverage of the service (IBGE, 2010);<br>b) intended public lighting expansion to 663 thousand lamps (PMSP, 2017) |
| **Water treatment sector-** treated water ($m^3$) | 2113 million $m^3$ (SABESP, 2015). | a) 100% water access rate (PMSP, 2010);<br>b) sewage treatment service coverage 75% (PMSP, 2010);<br>c) 2588 million m3 of produced water by 2030. |
| **Energy Sector-** aggregate sector demand (GWh) | 79 GWh (SEESP., 2015). | Historical rates replicated for 2030:<br>a) 0.8%per year of electricity demand decrease;<br>b) 16% per year NG consumption growth. |
| **Urban Mobility Sector-** # transported passengers | 297 billion passenger.km /year (pkm) (ANTP, 2016, n.d.; Metrô -Companhia do Metropolitano de São Paulo, 2013). | a) increase of 0.6% py in passenger's transportation (Comitê Intersetorial para a Política Municipal de Resíduos Sólidos, 2014; F. SEADE, 2017);<br>b) 327 billion passenger.km /year (pkm) |
| **Air Transport Sector-** # transported passengers | 18 million (pkm) (INFRAERO, 2017). | a) observed growth rate of 4.4% per year (from 2014/2016) (INFRAERO, 2017);<br>b) 2017-2030 national sector projections for air passenger transportation growth rate of 1.7% per year (EPE/MME), 2016[a]). |

## 4. Results and discussion

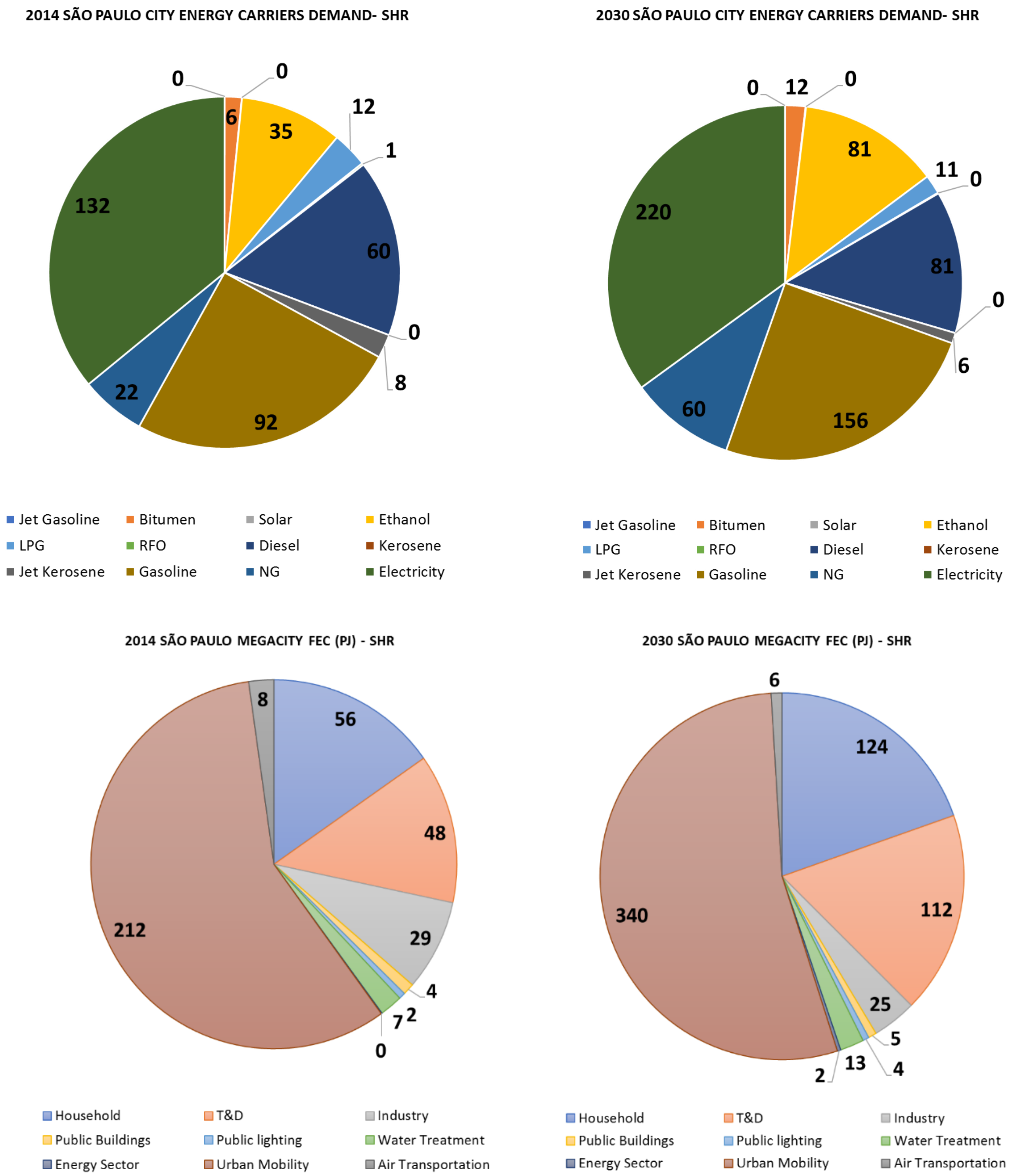
This section presents the selected urban and energy strategies modelled results for the São Paulo megacity UES. It first describes the city SHR results in terms of final energy consumption (FEC), final energy production (FEP), and GHG emissions. This is followed by the comparison with other three scenarios: SEP, SUP and SUEP. A quantification of the impact of each individual strategy on energy savings and avoided GHG emission is also presented.

## 4.1. City final energy consumption

According to São Paulo energy consumption historical data from 2006 to 2017 (MME, 2015; and SEESP, 2017, 2016, 2014, 2013a, 2012, 2010a, 2010b, 2008, 2007) there was a progressive increase in electricity demand in the building sector. On the other hand, all energy carriers consumed in the industry sector showed a significant decrease because Industry and AT sectors decreased their economic activity. In PL, current city policy for mercury and sodium lamps replacement by LEDs (PMSP, 2017) led to a decrease in energy intensity.

Regarding model results, in 2014 the highest consumed energy carrier was electricity with 36% (132 PJ), followed by gasoline 25% (92 PJ) and diesel (16%- 60 PJ). Together this represented 77% of São Paulo megacity FEC. By 2030, electricity maintains the lead with 220 PJ (35%) of total FEC, followed by gasoline (156 PJ- 25%), diesel and ethanol with 13% FEC share (81 PJ).

Regarding the city's most energy consuming sectors, in the 2014 UM was the most demanding sector (212 PJ; 58% of city FEC), followed by households (56 PJ; 15% of city FEC) and T&D (48 PJ; 13% of city FEC). This ranking will not be altered in 2030 with UM representing 340 PJ (54%,of city FEC), households with 20% of FEC (124 PJ), and T&D with 18% (112 PJ) (see Figure 5).




**.Figure 5- São Paulo FEC (sectors and energy sources) in PJ 2014-2030**

The model results on total FEC evolution for SHR 2014-2030 show an increase of 264 PJ from 2014 to 2030, representing a 72% growth (from 367 PJ to 630 PJ) until 2030. Regarding city RES consumption, in 2014 36% of FEC was RES (133 PJ) with the remaining 64% being fossil fuels (234 PJ). By 2030, fossil fuels energy consumption will reach around 61% (383 PJ) and RES 39% (247 PJ). This share of fossil fuels in FEC is mainly caused by the UM sector (road transport and AT with 76% and 100% of FEC supplied by fossil fuels). UM is followed by the ES (70% of ES sector FEC is fossil) and industry (67% of sector FEC is fossil).

The sectors with the highest RES consumption levels were: PB, PL and WT, all with 75% RES consumption. For these sectors the FEC available data only covered electricity. To determine RES and fossil FEC shares, the amounts of imported electricity were multiplied by 75% of RES and 25% of fossil participation, that corresponds to the 2014 real national electricity generation sources (see Table 4).

***Table 4- São Paulo city RES and fossil energy resources consumption (2014-2030) SHR scenario results***

| **Megacity Sectors** | **Type of energy resource** | **2014** | | **2030** | |
|---|---|---|---|---|---|
| | | **BY (PJ)** | **%** | **End Year (PJ)** | **%** |
| Households | Fossil | 25 | 45% | 74 | 60% |
| | *RES* | 31 | 55% | 50 | 40% |
| T&D | Fossil | 16 | 34% | 33 | 30% |
| | *RES* | 32 | 66% | 79 | 70% |
| Industry | Fossil | 19 | 67% | 19 | 78% |
| | *RES* | 10 | 33% | 5 | 22% |
| PB | Fossil | 1 | 25% | 1 | 25% |
| | *RES* | 3 | 75% | 3 | 75% |
| PL | Fossil | 1 | 25% | 1 | 25% |
| | *RES* | 2 | 75% | 3 | 75% |
| WT | Fossil | 2 | 25% | 3 | 25% |
| | *RES* | 6 | 75% | 10 | 75% |
| ES | Fossil | 0 | 70% | 2 | 96% |
| | *RES* | 0 | 30% | 0 | 4% |
| UM | Fossil | 161 | 76% | 243 | 72% |
| | *RES* | 51 | 24% | 97 | 28% |
| AT | Fossil | 8 | 100% | 6 | 100% |
| | *RES* | 0 | 0% | 0 | 0% |
| **Total** | **Fossil** | **234** | **64%** | **383** | **61%** |
| | ***RES*** | **133** | **36%** | **247** | **39%** |
| | **total** | **367** | **100%** | **630** | **100%** |

### 4.2. City electricity production

Regarding city electricity production, it is expected a steep reduction in the installed capacity due to the expected city power plants phase out in 2019 and 2029 (less 824 MW of installed capacity until 2030).

Figure **6** shows the city's local electricity production from 2014 to 2030, which is estimated to decrease by 89% in that period.

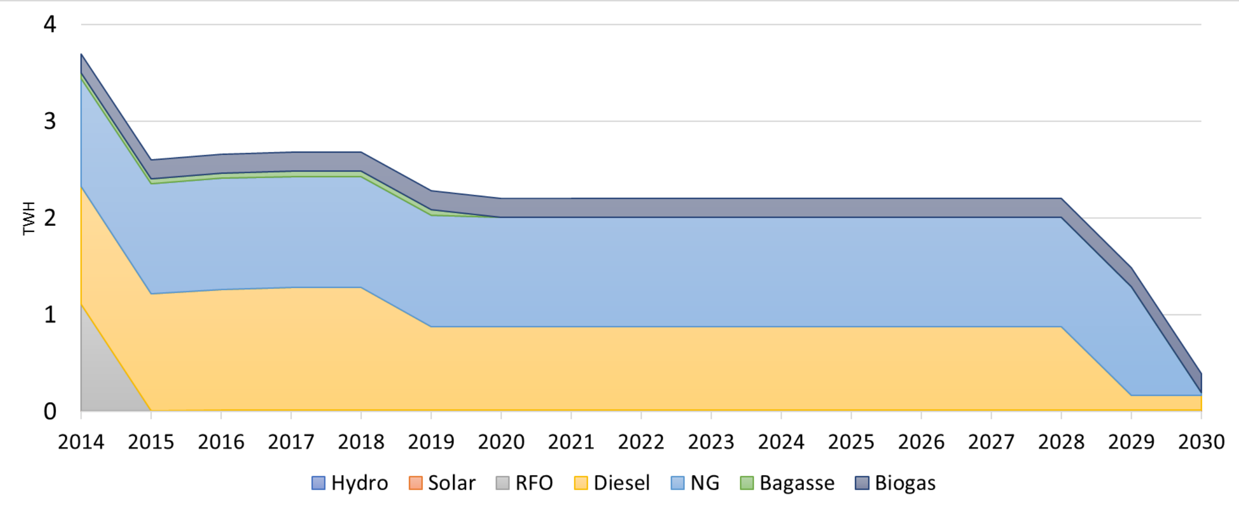



***Figure 6 - São Paulo local electricity production in SHR (2014-2030)***

The 2014 city power plants were mainly based on fossil energy resources (93% of the city electricity production). Diesel represented 33% of electricity production, NG 30% and RFO also 30%. When considering the power plants' phase out, electricty generation RES share increases up to 53% in 2030. However, the total electricity generated in the city decreases from 3.7 TWh to 0.4 TWh.

### 4.3. City GHG emissions

UM is the sector with the higher city GHG emissions contribution in 2014 (74% - 12 million metric ton $CO_2$e.). Followed by households with 9% of city GHG emissions, and industry with 7%. Gasoline is the energy carrier responsible for the highest share of GHG emissions (6.5 million metric ton $CO_2$e, that represent 40% of the emissions in 2014). Diesel contributed with 27% of 2014 GHG emissions, and NG with 12%.

***Table 5 - City GHG emissions growth expectations according to SHR scenario in Million Metric t$CO_2$e.***

| Performance metrics | SHR 2014 | SHR 2030 |
|---|---|---|
| **Total emissions** | 20.7 | 31.5 |
| **tCO2e/inhabitant** | 1.8 | 2.6 |

According to Table 5 and considering the SHR scenario, there will be an 43% increase in city GHG emissions until 2030 (from 20.7 million $tCO_2e$ up to 31.5 million $tCO_2e$). This means that, in terms of urban Public Policy analysis, the city is not going to comply with its Municipal Climate Change goals that set the objective of 30% emissions reduction from the 2003 city emissions per capita of 1.25 $tCO_2e$/inhabitant (Prefeitura do município de São Paulo, 2013). In 2014 the city's GHG per capita emissions were of 1.8 $tCO_2e$/inhabitant[9] and can reach 2.6 $tCO_2e$/inhabitant by 2030.

### 4.4. Urban and Energy Planning scenarios analysis

The scenarios were developed according to the type of UP or/and EP strategies included in each. To do so, the main outcomes intended for each strategy were classified as UP (for scenario SUP) or EP (for scenario SEP). If the main strategy intended outcome was energy savings (through EE) or GHG emissions reduction, the strategy was classified as an energy policy strategy, and thus allocated to its respective scenario SEP. All other kinds of strategies were allocated to urban planning scenario (SUP) (see scenario assumptions in Table 2). The UEP scenario (SUEP) is the SEP and SUP scenarios combination. It aims to demonstrate possible synergies of the UEP adoption approach.

Figure 7 and Table 6 shows scenarios results for FEC. The highest energy demand reduction was estimated in the SUEP scenario with a reduction of 74 PJ in FEC in 2030. This represents 12% less energy consumption than in the SHR scenario in 2030.

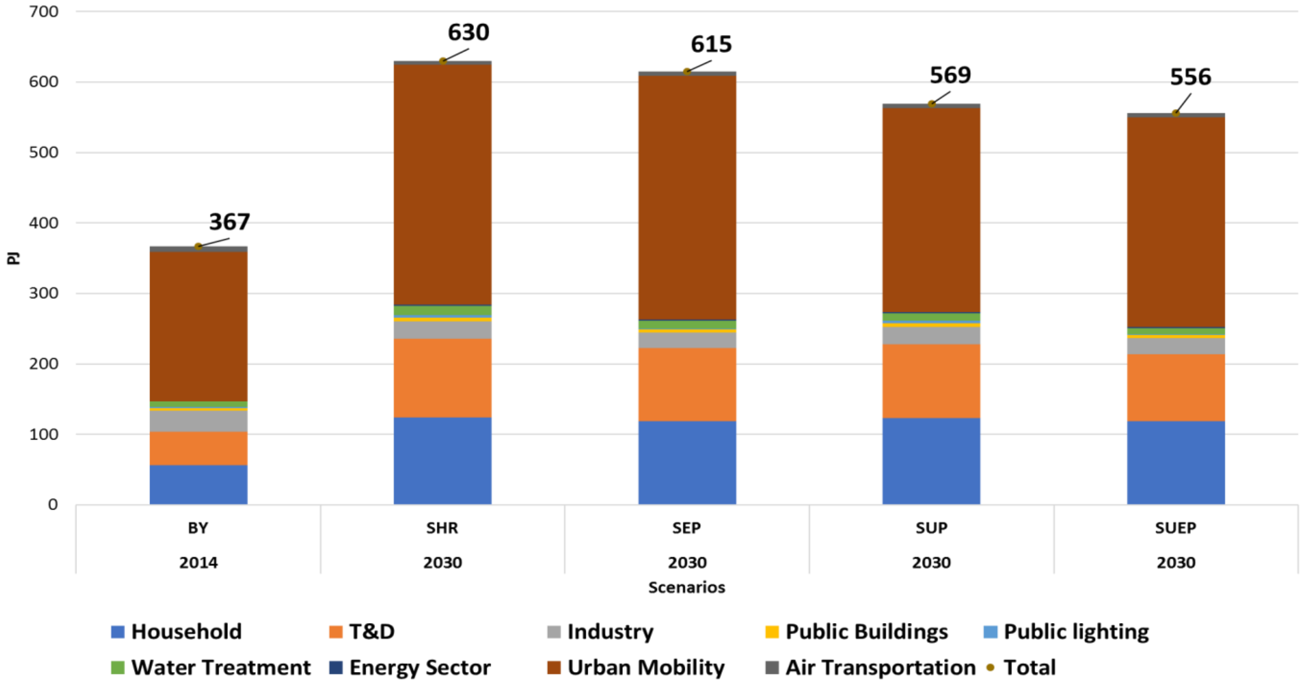



*Figure 7- Scenarios' FEC evolution 2014-2030 per sector*

[9] This index presents also grid electricity emission factor. If the national Brazilian grid emission factor is not considered, then the index values are: 1.4 $tCO_2e$/inhab. in 2014 and 1.9$tCO_2e$/inhab. in 2030.

For SUP and SEP scenarios (Table 6), UP strategies lead to 10% less FEC in 2030, whereas EP strategies result in only 2% less FEC compared to SHR.

***Table 6- FEC in the different scenarios compared with SHR.***

| **Sectors** | **FEC in 2030 compared to SHR (%)** | | | |
|---|---|---|---|---|
| | **BY x SHR** | **SHR x SEP** | **SHR x SUP** | **SHR x SUEP** |
| Households | 121% | -4% | 0% | -4% |
| T&D | 134% | -8% | -7% | -15% |
| Industry | -15% | -9% | 0% | -9% |
| PB | 23% | -10% | 0% | -10% |
| PL | 69% | -71% | 0% | -71% |
| WT | 81% | -17% | -20% | -36% |
| ES | 584% | 0% | 0% | 0% |
| UM | 61% | 2% | -15% | -13% |
| AT | -25% | 0% | 0% | 0% |
| **Total** | **72%** | **-2%** | **-10%** | **-12%** |

EP strategies have a minor contribution to FEC reduction in SEP because the strategies target mainly the buildings sector and electricity consumption. On the other hand, UP strategies in SUP scenario act on the city more energy intensive sector, UM. Moreover, within the mobility sector, the selected strategies deal with reduction of individual motorized mobility (cars) usage. Therefore, this study result is in line with scientific literature findings on UM importance for energy consumption patterns in cities (Marins, 2014; Ruparathna et al., 2017) and the fact that supporting PT and active mobility strategies are important policies to reach energy savings at city level. Figure 8 shows the city energy carrier consumption between scenarios in 2030.

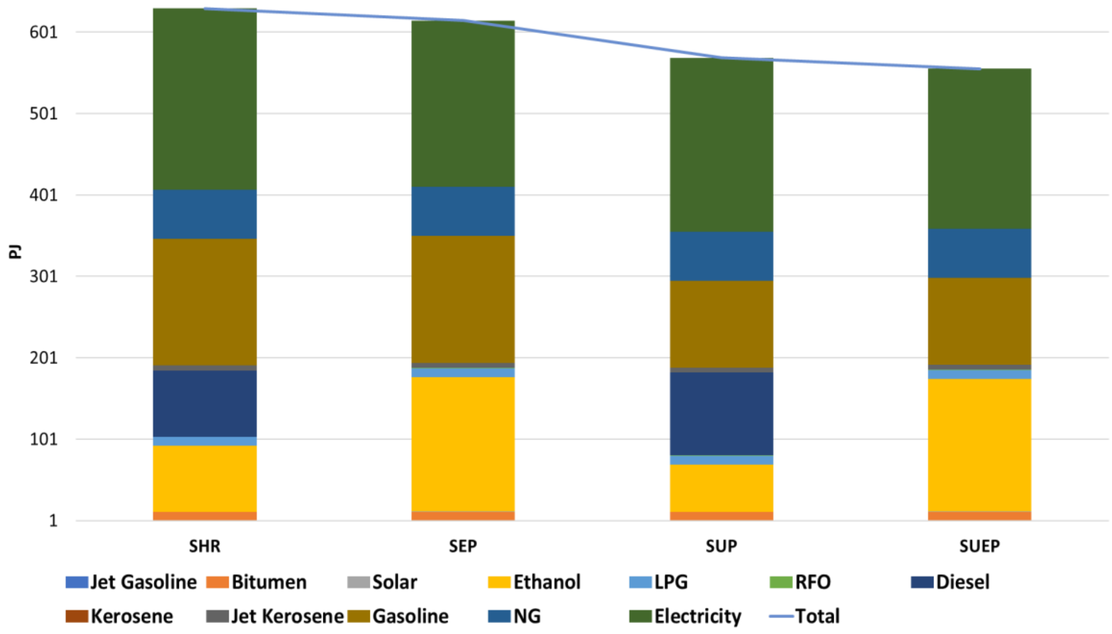



***Figure 8- City energy carrier conumsption per scenario in 2030***

Thus, strictly regarding energy savings, the level of synergies from integrating EP and UP strategies is low. The major contribution to energy saving indicator derives from UP strategies alone. Nonetheless, these results are interesting from an energy policy perspective since traditional EP do not consider the UP strategies potential to address energy savings outcomes.

Although, in general terms, the SUP scenario shows greater energy savings, SEP performed better in increasing the city's RES share. This result is related to the UM sector, since "No fossil fuels on PT"[10] strategy induced the highest impact in RES consumption. Consequently, a synergy that arises from integrating EP and UP is the possibility of reaching multi-results and goals.

Accordingly, regarding city RES energy consumption (Table 7), the SUEP scenario shows the highest RES share in 2030 with 310 PJ (56%), when compared to the other three scenarios.

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[10] An analysis of each strategy's impact is presented in the next section.

***Table 7- 2030 RES versus Fossil energy resource city demand per scenario***

| Sectors | Resource type | SHR | | SEP | | SUP | | SUEP | |
|---|---|---|---|---|---|---|---|---|---|
| | | PJ | % | PJ | % | PJ | % | PJ | % |
| Households | *Fossil* | 74 | 60% | 72 | 61% | 74 | 60% | 72 | 61% |
| | *RES* | 50 | 40% | 47 | 39% | 50 | 40% | 46 | 39% |
| T&D | *Fossil* | 33 | 30% | 31 | 30% | 32 | 30% | 29 | 31% |
| | *RES* | 79 | 70% | 72 | 70% | 73 | 70% | 66 | 69% |
| Industry | *Fossil* | 19 | 78% | 19 | 83% | 19 | 78% | 19 | 83% |
| | *RES* | 5 | 22% | 4 | 17% | 5 | 22% | 4 | 17% |
| PB | *Fossil* | 1 | 25% | 1 | 25% | 1 | 25% | 1 | 25% |
| | *RES* | 3 | 75% | 3 | 75% | 3 | 75% | 3 | 75% |
| PL | *Fossil* | 1 | 25% | 0 | 25% | 1 | 25% | 0 | 25% |
| | *RES* | 3 | 75% | 1 | 75% | 3 | 75% | 1 | 75% |
| WT | *Fossil* | 3 | 25% | 3 | 25% | 3 | 25% | 2 | 25% |
| | *RES* | 10 | 75% | 8 | 75% | 8 | 75% | 6 | 75% |
| ES | *Fossil* | 2 | 96% | 2 | 96% | 2 | 96% | 2 | 96% |
| | *RES* | 0 | 4% | 0 | 4% | 0 | 4% | 0 | 4% |
| UM | *Fossil* | 243 | 72% | 163 | 47% | 215 | 74% | 114 | 38% |
| | *RES* | 97 | 28% | 183 | 53% | 75 | 26% | 183 | 62% |
| AT | *Fossil* | 6 | 100% | 6 | 100% | 6 | 100% | 6 | 100% |
| | *RES* | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **Fossil** | **383** | **61%** | **297** | **48%** | **352** | **62%** | **246** | **44%** |
| | **RES** | **247** | **39%** | **318** | **52%** | **218** | **38%** | **310** | **56%** |
| | **Total** | **630** | **100%** | **615** | **100%** | **569** | **100%** | **556** | **100%** |

By combining UP and EP strategies (SUEP scenario) it is possible to achieve the best of both UP and EP impacts, i.e. an increase of the RES share when compared to the SEP (52% of RES participation) or SUP (38% of RES participation) scenarios. SUEP reaches 56% of RES city FEC in 2030, and a higher decrease of fossil FEC than if considering only UP or EP (Table 7).

The city per capita emissions are presented in Table 8. Electricity imports consider implicit GHG emissions corresponding to national electricity generation GHG emissions. Lower city GHG emissions levels occur by integrating urban and energy planning strategies (Table 8). Therefore, it is possible to conclude that for cities that want to fully harvest their climate change mitigation potential, integrating urban and energy planning strategies is an effective policy approach.

*Table 8- GHG emissions per scenario in Million metric $tCO_2e$.*

| Performance metrics | **2014** | **SHR-2030** | **SEP-2030** | **SUP-2030** | **SUEP-2030** |
|---|---|---|---|---|---|
| Total emissions | 20.7 | 31.5 | 25.8 | 29.0 | 22.2 |
| $tCO_2e$/inhabitant | 1.80 | 2.57 | 2.10 | 2.36 | 1.81 |

While in SEP and SUP GHG emissions increase 17% and 31% from 2014 values, respectively, in the SUEP scenario, GHG emissions in 2030 increase only 1% from 2014 values. When compared with SHR 2030 results, SUEP achieves a 30% GHG emission reduction (around 9.4 million metric $tCO_2e$ less), while SUP presents only a 8% reduction and SEP only a 18% reduction.

These differences in GHG emission decreases differences between SUP and SEP, although seemingly conflicted with energy savings results, are explained by the supply side policies allocation. Deploying city PV rooftop potential was considered to be an EP measure and thus was allocated in the SEP scenario, whereas all endogenous electricity production with biogas was allocated to SUP scenario (since it is motivated by the need to reduce the city's MSW flows).

This result can be considered as an important achievement of this study regarding the UP and EP strategies synergies quantification analysis, showing that policies that would not be prioritized by energy managers (since they save less energy), when combined with UP strategies can improve its impact and reduce city overall GHG emissions.

## 4.5. Role of individual UEP measures for overall city targets

Each strategy's impact analysis was made by combining data on energy savings and on GHG emission reduction. The results were divided into demand-side and supply-side. The demand-side results were divided in: (i) strategies that impact electricity savings and GHG emissions reductions (also related to the buildings sector in a broader perspective), and (ii) results that impact other city energy resources and respective GHG emissions reductions. Supply-side results are presented in terms of local electricity generation improvement and avoided GHG emissions.

Regarding the buildings sector, the estimated strategy with highest impact was the creation of new green areas achieving electricity savings of 8 PJ. This is equivalent to the sum of the PB and PL sectors energy consumption in 2014. Furthermore, it should be noted that these savings could even be greater if the new city green areas where located in more central areas than the ones currently planned. This strategy also demonstrated the largest contribution to GHG emissions reduction and highlights the need for the municipality necessity to consider defined energy and environmental targets in UP.

Figure 9 presents all building-oriented strategies and their results in terms of electricity savings and GHG emission reduction. The second-best performance strategy was the deployment of more efficient air conditioning units leading to 7 PJ of electricity savings and 5 000 $tCO_2e$ avoided. These results are in line with existing literature on the impacts of replacing old technologies with new ones (i.e. Feng and Wang, 2017; Heidarinejad et al., 2018).

Besides the previously mentioned strategies, it is worth to mention the natural lighting strategy potential for GHG emission reduction. This strategy has a modest performance in terms of electricity savings but is the third best strategy in terms of potentially reducing the buildings sector GHG emissions. This result is not usually discussed in the literature, since the emphasis is mainly placed on the potential of energy efficiency strategies (i.e., lamps technological replacement), see Coelho et al. (2018).

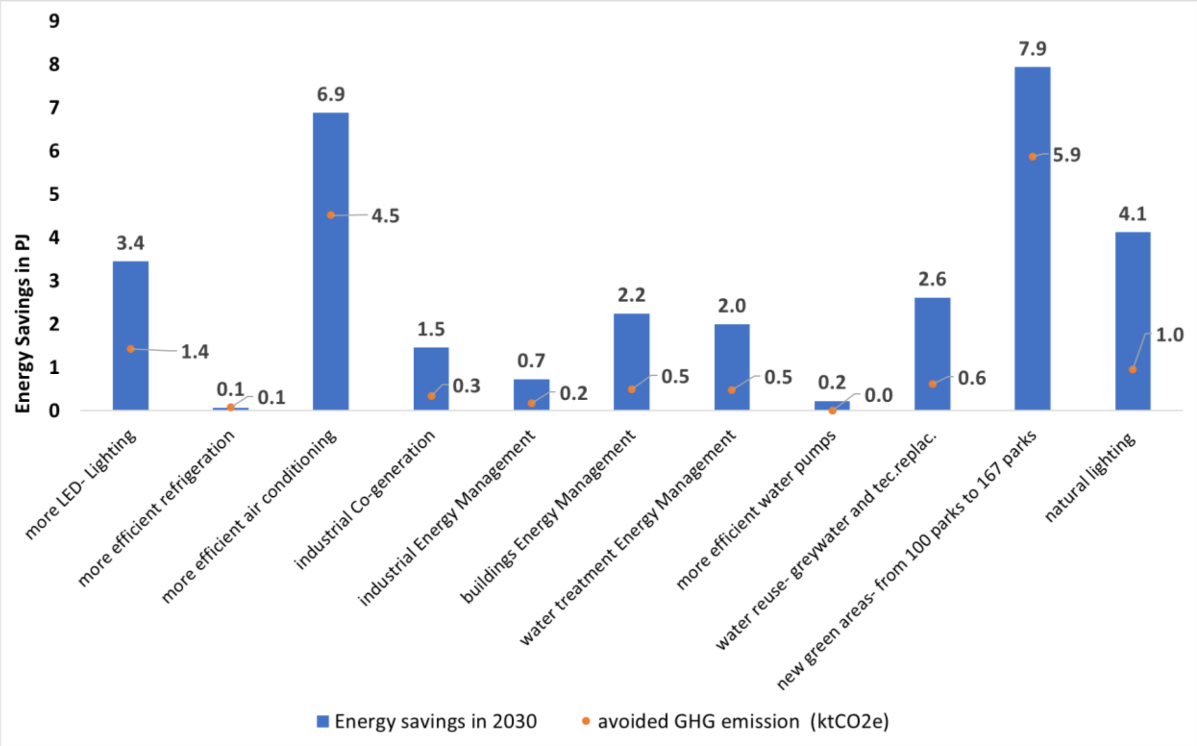


***Figure 9- Strategies impact on electricity savings and in avoided GHG emission (k $tCO_2e$.) – demand-side results***

Figure 10 presents the results for all other city energy carriers. The strategies presented target the UM sector and show the highest results in energy savings and GHG emissions reduction.

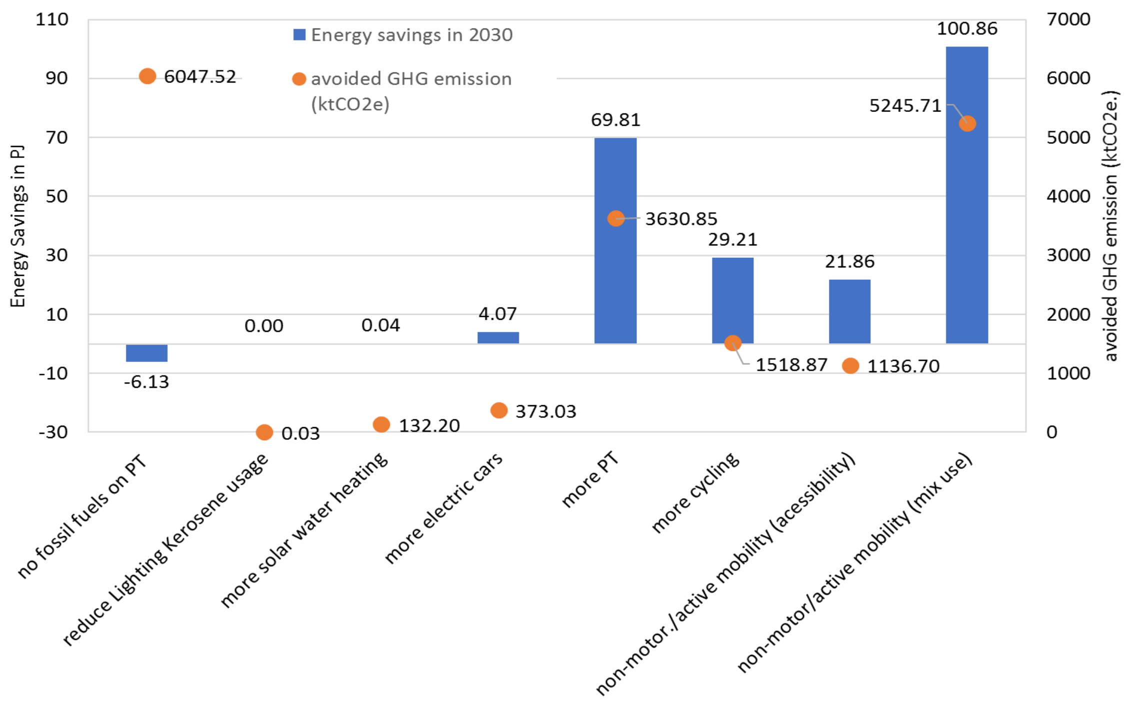


***Figure 10- Strategies impact on energy savings and avoided GHG emissions-demand-side results***

The ‘no fossil fuels on PT’ strategy contributed with the biggest share of emissions reduction, but it does not save energy. This strategy is expected to reduce around 6.5 million $tCO_2e$ in 2030. Nonetheless, it is going to use 6 PJ more energy due to diesel vehicles replacement with less efficient ethanol-based ones.

Most of the energy savings could be achieved by supporting the transition from individual transportation to active mobility modes and to public transport (Figure 10). Also, ‘more PT’ and ‘non-motorized transportation’ led to the second and third main GHG emissions reductions.

Regarding strategies that impact the supply-side, Table 9 presents the endogenous electricity and local generation obtained per scenario. SHR and SUP have negative variation of electricity production between 2014 and 2030 (due to the end-of-life of fossil fuel plants), while SEP and SUEP have an electricity production increase in the same period. This result is mainly due to PV deployment in household and T&D rooftops.

***Table 9- Endogenous electricity generation evolution per scenario***

| **Supply Side** | **TWh** | | **Variation (%)** |
|---|---|---|---|
| **Total electricity production** | **2014** | **2030** | **2014-2030** |
| **SHR** | 3.7 | 0.4 | -89% |
| **SEP** | 3.7 | 11.6 | 215% |
| **SUP** | 3.7 | 2.1 | -44% |
| **SUEP** | 3.7 | 13.3 | 261% |

Therefore, integrating UP and EP strategies can augment more positive results than obtained when only applying UP or EP strategies. Regarding the potential of reducing GHG emissions in the energy supply of the city, the main contribution comes from PV electricity generation. Note that local generation is going to generate also local emissions (not the case for PV). Nevertheless, the balance between local GHG emission generated by city electricity generation and GHG from electricity imports, shows a positive value (Figure 11).

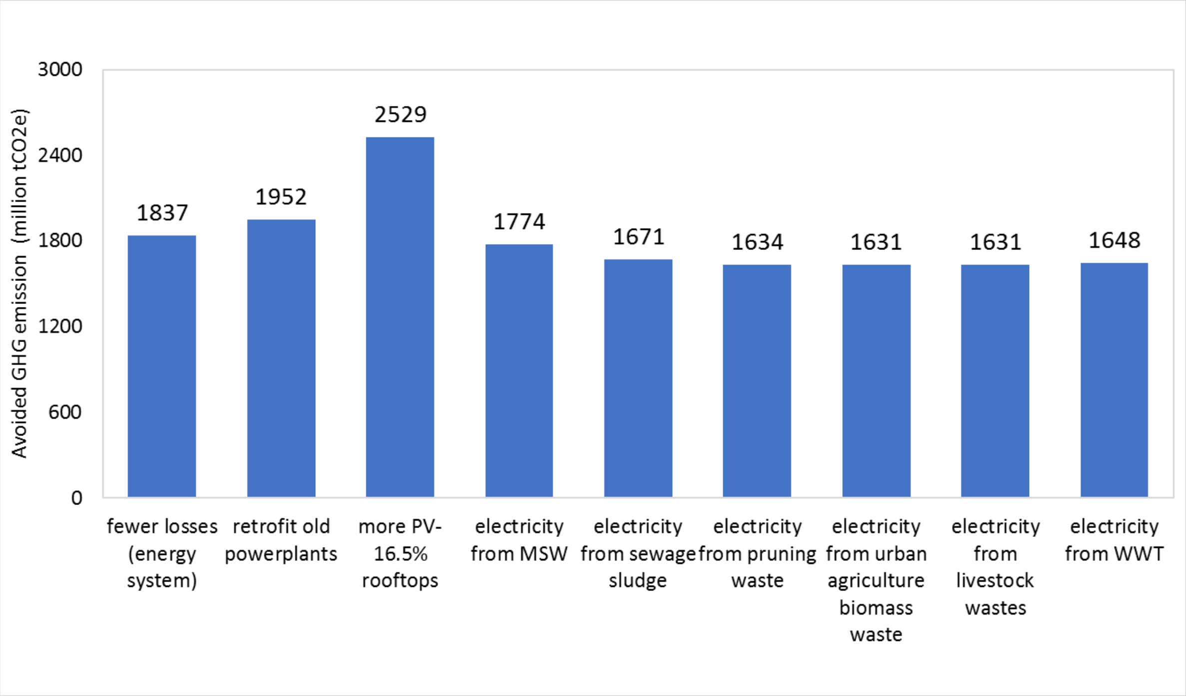


***Figure 11- Supply-side strategies implementation avoided GHG emissions***

For the first time a UEP holistic approach and quantitative analysis are presented for an existing megacity. Previous work discussing the integration between UP and EP has been made it in a theoretical non-specific way (i.e., Leduc and Van Kann, 2013). Nonetheless, Marins, (2014) presented an energy efficiency and emission potential impact assessment of integrating urban parameters and energy planning strategies for new districts and neighborhoods, and Permana et al. (2015) qualified a linear connection between UP and EP synergies, without providing quantitative estimates for such synergies.

Currently, available literature identifies UP and EP synergies with some degree of quantification, but without concrete application for a specific city. This paper presents a concrete quantification of such synergies between UP and EP, i.e. a quantification of the added value of UEP in a megacity system.

## 5. Conclusions and policy implications

UES coordination, and in particular, the UEP concept is a scientific area under development. Currently, there is a gap between energy demand and supply-side policy options integration, as well as between local and national climate change mitigation targets and corresponding policy measures. EP is in many cases considered separately from UP and subsequently combined synergies are not perceived nor harvested.

Therefore, current EP research work is mainly focused on technological solutions. Supply-side analysis tends to assess the feasibility of replacing fossil fuels energy resources with RES. On the other hand, demand-side studies normally focus on the technological replacement of appliances and other technologies, which means that mostly EE strategies are targeted. In this paper we argue that research should move beyond specific energy technologies, adopting a wider scope to consider also UP and energy conservation options.

Therefore, this paper presents an integrated solution matrix of energy and urban planning strategies. This holistic and multisectoral approach for UEP integrated synergies assessment was made by evaluating: (i) urban energy savings (i.e. focusing not only on energy efficiency, but also on energy conservation), (ii) GHG emission reductions, and (iii) local and RES electricity production opportunities/possibilities.

The matrix was applied to the São Paulo megacity (Brazil). A total of 29 UP and EP strategies and solutions were selected and simulated using the LEAP_SP model to envision São Paulo's future energy system (2014-2030) and to quantify possible synergies. These strategies were simulated over four scenarios, as follows: Historical Rates (SHR), Energy Policies strategies (SEP), Urban Policies strategies (SUP) and Urban and Energy Policies strategies (SUEP).

***Table 10- Scenarios comparison analysis on FEC, FEP, fossil share, RES share and GHG emission performance***

| SYNERGIES | Unit | SHR (a) | SEP (b) | (a-b)/a | SUP (c) | (a-c)/a | SUEP (d) | (a-d)/a | SEP+SUP | SUEP |
|---|---|---|---|---|---|---|---|---|---|---|
| FEC | PJ | 630 | 615 | 15 (2%) | 569 | 61 (10%) | 556 | 74 (12%) | 76 | **74** |
| | % | | | 2% | | 10% | | 12% | 12% | **12%** |
| *FOSSIL SHARE* | PJ | 383 | 297 | -86 | 352 | -31 | 246 | -137 | -117 | **-137** |
| | % | 61% | 48% | -12% | 62% | 1% | 44% | -17% | -11% | **-17%** |
| *RES SHARE* | PJ | 247 | 318 | -71 | 218 | 29 | 310 | 63 | -41 | **63** |
| | % | 39% | 52% | -12% | 38% | 1% | 56% | 17% | -11% | **17%** |
| FEP | PJ | 0.4 | 11.6 | 11.2 | 2.1 | 1.7 | 13.3 | 12.9 | 12.9 | **12.9** |
| | % | 100% | | 215% | | -44% | | 261% | 171% | **261%** |
| GHG EMISSIONS | PJ | 31.5 | 25.8 | 5.7 | 29.0 | 2.5 | 22.2 | 9.3 | 8.2 | **9.3** |
| | % | 100% | | 18% | | 8% | | 30% | 26% | **30%** |

Table 10 highlights our main results. The higher UEP potential when compared with individual UP and EP policies translates in 2030 energy savings in SUEP scenario of 12% compared to the SRH scenario. Although for FEC synergies between EP and UP integration are smaller than acting only on UP (UP leads to very similar FEC savings), for other indicators the results shows that UEP has clear benefits. This is the case of city RES share participation in 2030, from 11% up to 17% when UP and EP are simulated together. GHG emissions are reduced by 30% in SUEP in 2030 when comparing with SHR, and for SUP the GHG emissions reduction is less than 20%.

Furthermore, when UP and EP strategies are integrated, not only a more equitable effort-sharing is achieved for different city economic sectors, but also it is possible to simultaneously achieve different policy areas goals (e.g. climate mitigation, air quality, public health, well-being of residents). We have found that SUEP scenario has the best performance among other scenarios. Thus, when using a UEP approach, it is possible to further reduce FEC, increase RES share, increase city generated electricity and RES production and reduce GHG emissions.

However, implementing UEP is difficulted by the fact that it is not straightforward to classify policies, strategies and measures as energy or as urban planning. In this paper we presented one possible allocation method that highlights the importance of developing integrated UEP approaches.

Moreover, currently cities are still far from managing the implementation of such integrated planning. The different management departments make planning decisions that significantly affect cities' energy consumption. In some cases, the impact of their decisions on UES is not perceived. Therefore, we argue that the analysis made is necessary to determine core and best subjects and strategies for cities to comply with their energy and climate goals. In other words, the presented systematization provides a better understanding of the full city system. It also enables managers to think and organize the different departments, areas, and stakeholders that must be enrolled for effective strategies' implementation.

Other application of the proposed integrated solutions matrix of energy and urban planning strategies can be the support of recent initiatives for city rankings on energy consumption and RES-based electricity. These rankings require some clarification in the used methodologies especially regarding defining energy system boundaries. Frequently cities report their RES-based electricity initiatives using a simple proportion of their electricity consumption using the national electricity production matrix. Therefore, a city as São Paulo, located in a country with very high RES-based electricity will automatically be considered with high performance in that aspect. However, as we have shown in this paper, the electricity generation in São Paulo is in fact non-RES based. Our integrated solutions matrix supports cities in assessing their energy system (and boundaries) in a more comprehensive format.

Regarding research limitations, the apportionment of measures and strategies as UP or EP, shows some uncertainty, as it can be made in different forms as previously discussed. Moreover, for some sectors (energy and AT) and some energy end-uses and technologies (i.e. cooking, vertical transportation, technological improvement and modal shifts for motorcycle, trains and subways) it was not possible to simulate any strategies due to lack of detailed data. Other limitations include the consideration of only one socio-economic development pathway for São Paulo city in all modelled scenarios. This means that the city services coverage level was assumed static until 2030, when in reality they could show performance variability. Finally, the present work did not include a cost-benefit analysis for the selected strategies.

Regarding the simulation model limitations, like most technology models, LEAP_SP does not consider in detail consumption behavior information (e.g. rebound effect). Some model parameters have little robustness due to limited data available for particular city activities. LEAP_SP model was developed using the best information available which dated to 2009 regarding: location and energy end-use types, technology-related information, and other demand drivers. It would be necessary to update this when new information is available. The model represents the aggregated city energy demand and supply evolution. Therefore, it does not consider its sub-city areas and neighborhoods economic, social and energy consumption’s different characteristics.

The proposed matrix established guidelines that can be used as UP orientation for defining energy and environmental targets. This allows cities to reach sustainability goals in a holistic manner, improving current segmented and mono-goal practices city planning. Moreover, the method could be applied to scenario planning and envisioning based on different stakeholders’ inputs. This would allow different factors to be comparable and considered to build more coherent urban and energy systems.

The method would also be useful to support municipalities developing more aligned energy plans and overall city master plans. This would also represent a very innovative action, in particular for the Brazilian context. Finally, future work on UEP should address cost-benefit analysis and cities’ energy embodied needs. UM energy consumption hegemony can possibly be reduced if cities energy consumption on embodied materials and services is quantified.

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# 8. Annexes

## 8.1. ANNEX A – Overview of main data sources used for the LEAP_SP model development

Data used for the base year (2014) is public and available in public statistics. An extrapolation was made to project the evolution of energy use until 2030. The main used documents for this, were the National and State Energy Plans and other related documents (CEPE, 2012; Empresa de Pesquisa Energética (EPE)/ Ministério das Minas e Energia (MME), 2017, 2016b, 2016c, 2007, Ministério de Minas e Energia, 2015, 2011, Secretaria de Energia do Estado de SP., 2015a, 2013b, 2011), as well as all available energy statistical yearbook of energy consumption per São Paulo state municipality (Secretaria de Energia do Estado de SP., 2017, 2016, 2015, 2014, 2013, 2012, 2011, 2010, 2009, 2008, 2007), and the city sectorial Urban Policies and laws, i.e., sanitation, urban solid waste, the city master plan and the mobility plan (Prefeitura de São Paulo, 2014; Prefeitura do município de São Paulo, 2016; Prefeitura do Município de São Paulo, 2010; REDE NOSSA SÃO PAULO, 2014).

The city reference energy system for the 2014 used an extensive data compilation from the following sources (Associação Nacional de Transportes Públicos - ANTP, 2016; CEPE, 2012; Comitê Intersetorial para a Política Municipal de Resíduos Sólidos, 2014; Eletrobras and PROCEL-INFO, 2007; Metrô -Companhia do Metropolitano de São Paulo, 2013; Prefeitura de São Paulo, 2014; Prefeitura do município de São Paulo, 2016; SEADE, 2017; Secretaria de Energia do Estado de SP., 2015b, 2011; Tourte, n.d.). A validation was made of all the compiled information by cross-referencing additional official sources of information, such as (Empresa de Pesquisa Energética (EPE) / Ministério das Minas e Energia (MME), 2007; Ministério de Minas e Energia, 2011).

Plus, LEAP_SP model case study accounts with the imported electricity from the national grid and respective emission factor, and with real local electricity production. The upstream energy system is not considered in this research. Regarding bunker fuels, the city has no kind of river navigation (there is no sea in the city) and it thus was only taken into consideration the city airport fuel consumption (Congonhas airport), for the base year (2014).

## 8.2. ANNEX B – LEAP_SP Structure – demand side

| Economic Sector | Analyzed Energy Services*/ Subsectors | Considered End Uses/ Technologies* | Considered Energy Resources and carriers |
|---|---|---|---|
| Households, T&D and PB | Lighting | Incandescent lamp; fluorescent lamp; LED lamp; lighting kerosene. | Electricity; Lighting kerosene; Solar; LPG; NG. |
| | Refrigeration | Efficient refrigerators; Inefficient refrigerators. | |
| | Water Heating | Electric boiler; NG boiler, solar boiler; LGP boiler. | |
| | Cooling | Efficient air conditioning; inefficient air conditioning | |
| | Entertainment | Tv; radio; laptop. | |
| | Electronic equipment/devices | Iron; washing machine and others. | |
| | Cooking | LGP; NG. | |
| | Vertical Transportation[11] | Elevator. | |
| | Water Pumping[12] | Efficient pump; inefficient pump. | |
| Industry | **Extractive industry; **Transformation industry; **Public Utilities industry. | Energy Intensity of each industrial segment (PJ/Gross Value Added). | Electricity; RFO; Bitumen; LPG; NG. |
| PL | Lighting | Sodium lamp; mercury lamp; LED lamp. | Electricity |
| WT | Water Distribution | Efficient pump; inefficient pump. | Electricity |
| | Sewage Collection | Efficient pump; inefficient pump. | |
| | Sewage Treatment | Electronic equipment and machines | |
| | Lighting. | Incandescent lamp; fluorescent lamp; LED lamp. | |
| ES | Without sector[13] | n/a | Electricity; NG |
| UM | Individual Transportation | Cars and Taxis: gasoline, ethanol, Flex (gasoline and/or ethanol), NG and electrical; Motorcycle: gasoline. | Gasoline; Diesel; NG; Ethanol; Electricity. |
| | Public Transportation | Buses: diesel, ethanol, hybrid (diesel and/or electrical) and electrical; Train and Subway: electrical. | |
| | Non-motorized transportation | Active transportation: bicycle and foot | |
| AT | Without sector | n/a | Jet gasoline Jet kerosene. |

* the information on the city's energy services was configured as a coverage rate of each service in the city, and was determined according to official data collected from, mainly (Brasil, 2010; Comitê Intersetorial

[11] Applied only for T&d and PB.
[12] Applied only for T&d and PB.
[13] For the ES and the AT sector there are no subsector analyses, just aggregate energy consumption data was inputted inside the model

para a Política Municipal de Resíduos Sólidos, 2014; Eletrobras and PROCEL-INFO, 2007; INFRAERO, 2017; Prefeitura de São Paulo, 2014; Prefeitura do município de São Paulo, 2016; Prefeitura do Município de São Paulo, 2010). Likewise, information on energy end-use technologies was configured according to the ownership rates observed in the Southeast region, according to data presented in (Eletrobras and PROCEL-INFO, 2007).

** in 2014 there were around 30,623 industries (SMDU and Deinfo, 2014) located in the city. For the purpose of this paper, they were grouped in 3 industry segments: Extractive; Transformation and Public Utilities industries. These categories were taken from the 'Instituto Brasileiro de Geografia e Estatística' (IBGE), 2007).

### 8.3. ANNEX C - Detailed assumptions for modelling the Integrated Solutions Matrix in LEAP_SP

For modelling in LEAP_SP each one of the strategies of the Integrated Solutions Matrix presented in Table 2 it was necessary to perform intensive data processing combined with quantitative assumptions, as detailed in this annex (plus annex D and E).

i) No fossil fuels on PT strategy (UM sector) - eliminating diesel fuel consumption until 2030 for the megacity PT (Buses modal) as proposed by the municipal Climate Change Policy (PMSP, 2009) and its demand was replaced by ethanol fuel-based buses;

ii) No usage of Lighting Kerosene for household sector - fully replacing the consumption of this fuel until 2030 with electricity;

iii) Strategies on technological replacement (more LED; more efficient refrigeration; more efficient air-conditioning and more efficient water pumps as in Table 2) by doubling the ownership rate of target technologies from what was envisioned by national official governmental forecast (MME, 2016a) or from the BY ownership rate (Eletrobras and PROCEL-INFO, 2007). In cases like 'more efficient water pumps', where no data was available, it was considered that the most efficient technology options for this end-uses would represent at least 10% of the respective technology stock by 2030[14];

iv) Public Lighting with LED - all city PL use LED technology by 2030, as aimed by the current city ILUME program (2014);

v) More Solar water heating - double growth rate from what was envisioned by national official governmental forecast (MME, 2016a);

vi) Industry co-generation - electricity saving potential of 20% of total electricity consumption is achieved in 2030 (IEA, 2017);

vii) Energy Management strategies: for Industry and Buildings considered 10% of energy savings based on (Empresa de Pesquisa Energética (EPE) / Ministério das Minas e Energia (MME), 2007), and for the Water Treatment sector was considered that 15% of energy savings can be achieved in 2030 (Ministério de Minas e Energia, 2011);

[14] The intensities of the efficient appliances were determined according to the Brazilian Labeling Program (Programa Brasileiro de Etiquetagem- PBE) for the most efficient classification use regarding the same pattern of appliance and service, analysis on the various kind of appliances possess was not take into consideration.

viii) Water Reuse of greywater and dual flush considered for Household, T&D and Public sectors, translated as water savings around 670 million $m^3$ per year (Proença et al., 2011) which lead to a lower demand of pumping water for distribution in Buildings with corresponding energy savings;

ix) New Green Areas - the effect of creating new green areas in the city and its impact on cooling (simulated as a reduction on the use of air-conditioning) was considered based on the current City Master Plan (2014) that targets the creation of 67 new parks in the city (from 100 parks in the BY to 167 parks in 2030). GIS software and data on established green areas in the city and the new envisioned ones were used. This data was crossed with the information on T&S and Household city zones to estimate the T&S and Household areas impacted by the cooling effect of current and future green areas. It was considered a maximum range of cooling effect of 800 meters from the green areas with a maximum effect of 10% of energy savings and a 0.75 decay factor impact for every 200 m of distance (Shashua-Bar and Hoffman, 2000). The size of the green areas was not considered. Table 11 presents the percentage of areas impacted by the cooling effect of current and future new green areas creation in São Paulo. Figure 12 presents the T&D, household and green areas location in the city, and the areas impacted (ranges of blue and red) and non-impacted areas (grey color) per range of influence:

***Table 11- Household and T&S $m^2$ green area proximity evolution according to city Master Plan Goal***

| Household $m^2$ distant (…) from current green areas. | % in the BY | Household $m^2$ distant (…) from new planned green areas. | % in 2030 |
|---|---|---|---|
| 200 m | 1.6% | 200 m | 1.7% |
| 400 m | 1.9% | 400 m | 2.7% |
| 600 m | 1.8% | 600 m | 3.2% |
| 800 m | 1.8% | 800 m | 3.6% |
| **total** | **8%** | **total** | **12%** |
| T&S $m^2$ distant (…) from current green areas. | % in the BY | T&S $m^2$ distant (…) from new green areas | % in 2030 |
| 200 m | 3.0% | 200 m | 8.5% |
| 400 m | 2.9% | 400 m | 11.4% |
| 600 m | 2.6% | 600 m | 12.7% |
| 800 m | 2.6% | 800 m | 11.5% |
| **total** | **11%** | **total** | **44%** |

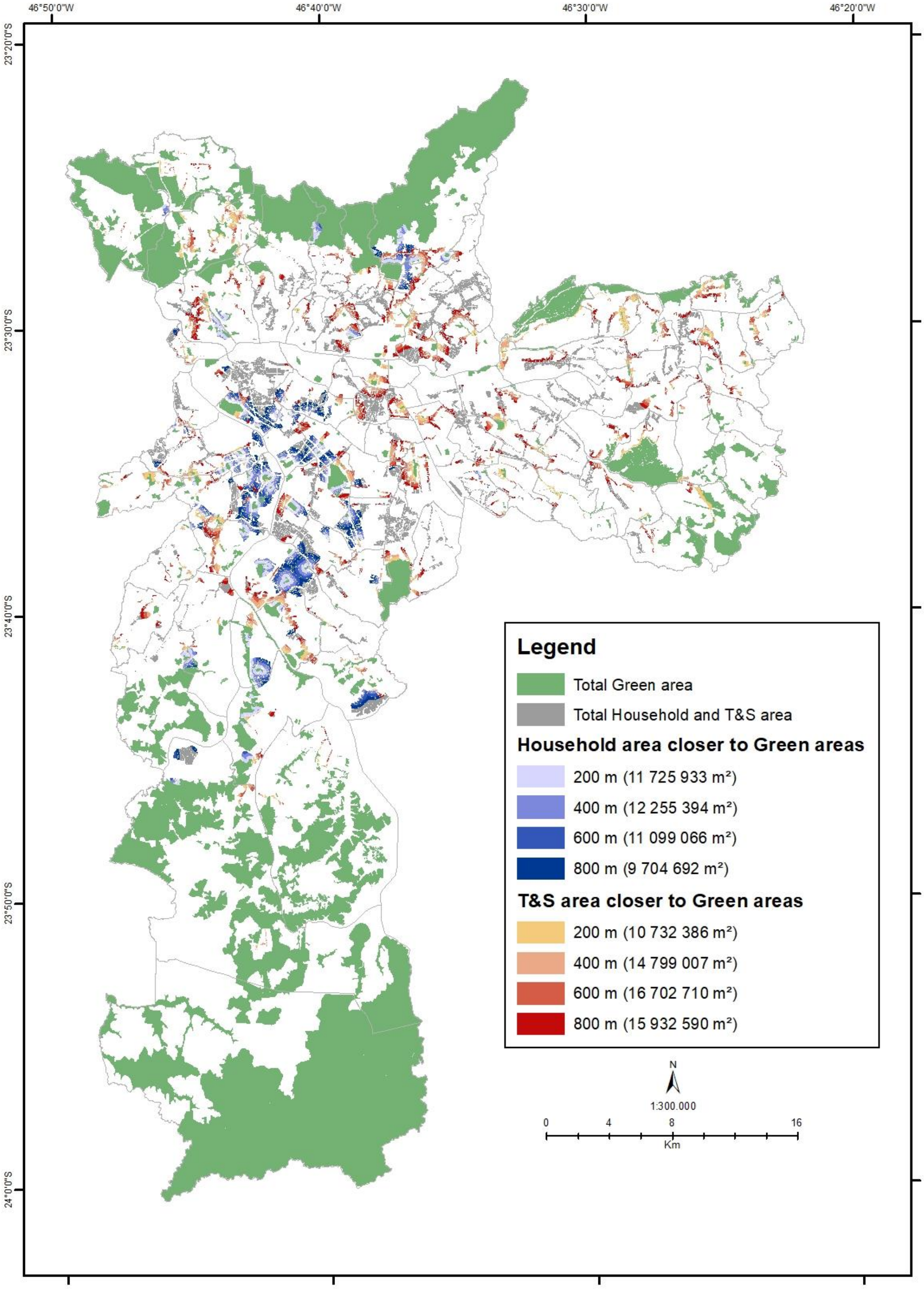


***Figure 12- São Paulo city map with the range of influence of Green Areas (from less than 200 meters until a maximum of 800m of distance) in the household and T&D areas.***

x) Natural Lighting through passive architecture - for T&S sector was considered 30% energy savings (this sector has a greater economy potential because of working hours and daytime) and 15% of energy savings for Households;

xi) More electrical cars - an electrification of the city's taxi fleet was assumed;

xii) More PT and more Cycling strategies - the city Mobility Plan targets were considered, namely 70% of transported passengers using PT and 30% with individual transportation (BY mobility share was of 56% for public transportation and 44% for individual transportation). For cycling the target is going from 0.6% of trips made by bicycles to 3.2% (Prefeitura do município de São Paulo, 2016);

xiii) Non-motorized or Active mobility (accessibility and mix-use impact) – it was assumed that 7% of the São Paulo population car drives physically fit will switch from cars to bikes. The estimation of the São Paulo population car drives physically fit was made by subtracting the % of handicapped São Paulo individuals (24% of the city population, according to the last city census) and by considering only the individuals that were under 15 and above 49 years, i.e. 1 887 225 passengers (Marins, 2014).

Regarding supply-side strategies (Fewer Losses- energy system, Retrofit Old powerplants, More PV- 16.5% rooftops T&D and Household, Electricity from MSW-biodigester, Electricity from sewage sludge- biodigester, Electricity from pruning waste, Electricity from urban agriculture biomass waste, Electricity from livestock wastes and, Electricity from WWT). Table 13 presents the summary of approach and assumption used to assess the RES and local São Paulo city electricity generation potential.

The model results for the RES power plants energy potential considers the addition of a biodigester for 99 kW biogas from the city biomass livestock waste; one biodigester of 3430 kW biogas of biomass from pruning; 3 biodigesters of 58157 kW biogas from MSW; two biodigesters for 120 kW from biomass of urban agriculture waste; 6 biodigesters to 48840 kW of sewage biogas production and 174471 kW and 3 biodigesters for WWT cogeneration; and 5180 MW from PV.

## 8.4. ANNEX D - São Paulo's city electricity generation installed capacity according to power plants age

*Table 12 - São Paulo's city electricity generation installed capacity according to power plants age, 2014 (Agência Nacional de Energia Elétrica - Aneel, 2017).*

| **Power Plants** | **More than 20 years** | | **At least 20 years** | | **At least 10 years** | | **< 1 year** | |
|---|---|---|---|---|---|---|---|---|
| | **Nº. Units** | **Capacity (kW)** | **Nº. Units** | **Capacity (kW)** | **Nº. Units** | **Capacity (kW)** | **Nº. Units** | **Capacity (kW)** |
| **Period** | **(…)-1993** | | **1994-2003** | | **2004-2014** | | **2015-2017** | |
| RFO | 1 | 190000 | n/a | n/a | n/a | n/a | n/a | n/a |
| Diesel Oil | 8 | 17407 | 37 | 69233 | 105 | 123722 | 24 | 25975 |
| NG | n/a | n/a | 3 | 8385 | 11 | 416150 | 5 | 12478 |
| Bagasse | 1 | 27 | n/a | n/a | 2 | 7500 | n/a | n/a |
| Biogas - MSW | n/a | n/a | n/a | n/a | 2 | 26184 | n/a | n/a |
| Micro Hydro | 1 | 2240 | 0 | 0 | n/a | n/a | n/a | n/a |
| Solar | n/a | n/a | 2 | 15 | n/a | n/a | 1 | 2242 |
| **Total** | **11** | **209674** | **42** | **77633** | **120** | **573556** | **30** | **40695** |

## 8.5. ANNEX E – Assumptions used to assess the São Paulo RES and endogenous potential

***Table 13- Summary of approach and assumptions to assess the São Paulo RES and endogenous potential***

| RES and Endogenous source | Approach and assumptions used |
|---|---|
| PV potential | a) city average annual incident solar radiation per season of 4.59 $kWh/m_2$.day (Secretaria de Energia do Estado de SP., 2013b);<br>b) available, useful and economically feasible rooftop area of 16,5% (EPE, 2014); c) 357 million $m^2$ in 2014 (total T&D and Households $m^2$) (SMDU and Deinfo, 2014);<br>d) PV efficiency of 16% (Greenpeace, 2016) and 80% of system performance ratio (EPE, 2014; Konzen, 2014). |
| Biogas production from MSW | a) 6300 t/day of MSW generated in BY (REDE NOSSA SÃO PAULO, 2014);<br>b) 4597 t/day in 2030 (the new number was determined considering the population growth rate expected for São Paulo and the implementation and success of the MSW Policy wastes reduction target);<br>c) one ton of Volatile organic compounds (VOC) produces about 400 $m^3$ of $CH_{4;}$<br>d) Methane, in normal conditions, has low calorific value (LCV) of 9.9 kWh /$m^3$;<br>e) 23% of VOC in food residues (Rocha, 2016). |
| Biogas production from urban agriculture biomass waste | a) 28 million kg of produced food (yearly average food production from perennial and temporary kinds of crops) (CATI/IEA, 2009);<br>b) 8% of waste production (Comitê Intersetorial para a Política Municipal de Resíduos Sólidos, 2014);<br>c) 2 kt of food waste for biogas production[15]. |
| Biogas production from livestock wastes | a) methane potential estimation considered the kind of animals breeding: oxen (206 heads, (IBGE, 2014)), poultry (148590 heads (IBGE, 2014)), and pigs (734 heads (IBGE, 2014));<br>b) methane flow equation used:<br>$QCH_4(m^3/h)$= {[(number of days/month) * (total heads (th) * total manure (tm) * biogas production (bp) * biogas methane concentration (bmc) )]/ methane specific volume (msv)}[16] |
| Biogas production from pruning biomass wastes | a) 140 t/day of waste (Comitê Intersetorial para a Política Municipal de Resíduos Sólidos, 2014);<br>b) 909 t/day by 2030 (considered a linear relation between the new amount of green areas $m^2$ and observed pruning wastes from the BY, considering moving from 100 parks to 167 parks). |
| Biogas production from WWT and from sewage sludge | a) current sewage treatment city capacity of 3,3$m^3$/s (two sewage treatment plants that are inside the city limits named ETE Novo Mundo e ETE São Miguel);<br>b) sewage treatment city capacity of 10,5 $m^3$/s in 2030.<br>c) 1$m^3$ of sewage can generate 85,6 NL of biogas;<br>d) biogas PCI of 6,47 kWh/m3;<br>e) 33% of conversion efficiency (Silveira et al., 2015);<br>f) 805 t/day of sewage sludge in BY;<br>g) 1t of sewage sludge has 70% of VOC;<br>h) 0.8$m^3$/ kg of destroyed VOC (Silveira et al., 2015). |
| Retrofit old power plants | a) CGH increasing capacity according to Bianchi (2002);<br>b) Diesel, NG and Bagasse retrofit to increase useful life to ensuring the installed capacity for more time and non-closing in the analyzed period. |
| Fewer Losses | a) goal of losses should be around 10% (Bermann, 2007). |

[15] Given lack of update data and small percentage of participation of this source in the electricity generation, this potential does not surmise with evolutions over the years until 2030, the same was applied for livestock wastes.

[16] Number of days considered were 365, the specific values can be found in (Barbosa and Langer, 2011; COLUNA, 2016; CETESB, 2017; Møller et al., 2004)