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Lowering energy vulnerability in São Paulo by increasing the use of gas

Luis Antonio Bittar Venturi [1*], Alexandre Vastella F.de Melo [1], David Shiling Tsai [1], Greta Yale Lima dos Santos [1], Pedro Paulo F. da Silva [2], Felipe Ferraz Machado [2], Gabriel José Mendonça Azevedo [1], Edmilson Moutinho dos Santos [2]

[1] *Department of Geography, University of São Paulo, S.Paulo, Brazil*
[2] *Energy and Environment Institute, University of São Paulo, S.Paulo, Brazil*

Abstract

In a context of pressing demand for energy in an increasing urbanized world, energy supply and vulnerability are momentous issues. A plethora of authors addresses this matter, being widely accepted that the more different sources of energy are available, the less vulnerable is an area. In Sao Paulo, electricity is highly predominant in households, being gas comparatively underused. Apart from this uneven energy supply, electrical energy is almost totally distributed by overhead grids constantly affected by gales, storms, toppling trees, traffic accidents, etc. Consequently, São Paulo is an energy vulnerable city, which is expressed by frequency and duration of outages. This being said, this research aims to prove the hypothesis that increasing gas use would lower energy vulnerability. We defined the concept of vulnerability and chose indicators that fit best the São Paulo reality: 1) Dimension of an area served by a power substation. 2) Availability of different sources. 3) Distance from avenues. 4) Proximity to priority areas. 5) Density of trees along streets. By crossing these indicators and attributing to them different weights, we established four classes of energy vulnerability: *very high, high, medium* and *low.* Then, we mapped all residential areas according to these classes. Finally, we changed the variable 2 by rising artificially the use of gas to draw a scenario where electricity and gas are equitably used. In this testing scenario, we could clearly observe a decreasing in *very high* and *high* vulnerability areas in São Paulo, whereas *medium* and *low* areas grew, corroborating the hypothesis.

Keywords: Electricity; Gas; Energy Vulnerability

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[*] Corresponding author. *E-mail address:* luisgeo@usp.br

1. Introduction

Considering that around 54 % of world population live in cities (United Nations, 2016), energy supply is essential to guarantee all human activities. Hence, discussing energy vulnerability in cities is a momentous issue. Many authors studied the concept of energy vulnerability proposing different indicators to assess it; however, few tried to apply the concept to an empirical urban reality.

Maliszewski and Perrings (2012) mapped central Phoenix (USA) focusing on energy *resilience* (as the speed of return to equilibrium following perturbation), not vulnerability itself. Furthermore, the wide diversity of cities requires us to choose different indicators of energy vulnerability. In an immense metropolis of a developing country, in the likes of São Paulo with more than 21 million inhabitants, some indicators may be more relevant than others may, but in all cases, having more than one energy source is unanimously preferable.

Given that, this study aims to fill a gap concerning the application of energy vulnerability concept in the city of São Paulo through mapping techniques and projecting a scenario of increasing use of gas to verify how vulnerability may change.

Following this introduction, we discuss the concept of energy vulnerability and its indicators according to different authors, choosing those more suitable to the São Paulo context. We, then, explain the mapping methodology we created. By attributing to indicators different weights and crossing them in a matrix, we framed four classes of vulnerability and applied them to the city of São Paulo through mapping techniques, focusing residential areas only.

After that, we validated the four classes by collating some sample areas of each class with a table of frequency and duration of energy outages. By doing so, we could assure that what we called as *very high* vulnerability is an area that really faced more energy outages, whereas areas classed as *low* vulnerability were affected by less energy outages.

Next, we then framed a second map projecting a scenario of equal use of electricity and gas in houses to verify how areas of each class may change.

Following that, we draw conclusions.

1.1. Energy vulnerability conceptual background

The concept of vulnerability is largely used and embraces such a wealth of ideas. Indeed, it is used in very different ways by scholars from distinct areas and even within the same area (Füssel, 2007). A first search in Science Direct website shows more than 110 articles using this concept in wide range of fields, from neuroscience to environmental changes.

According to Adger (2006), vulnerability has been a powerful analytical tool for describing states of susceptibility to harm, powerlessness, and marginality of both physical and social systems, and for guiding normative analysis. Despite being widely used, there is no consensual comprehension of it. (Gallopin, 2006). Calvo and Dercon (2005) say that the term vulnerability comes from the Latin “vulnerare” which means, “to wound” and it is clearly related to dangers or threats.

Turner et al. (2003) define vulnerability as "the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress / stressor" (p. 8.074). This author links vulnerability with resilience concept, which is the capacity of recovering after being harmed by a perturbation. The more resilient is a system, the less vulnerable it is.

Authors always link vulnerability to something that can disturb the system, which is a perturbation, hazard, harm or disturbance to name a few (Turner et al., 2003; Artigues, 2008; Gallopin, 2006). Indeed, Adger (2006) notices that all formulation has something about exposition of a system to a stress, and the sensitivity and adaptive capacity of the same system.

Regarding possible stresses that may affect an energy system, Laldjebaev et al. (2018) cite, for example, insufficient energy production capacity, scarce transparency in the power sector, small regional cooperation in energy and water resources sharing, and inadequate financial resources. Jansen (2009) highlights technical failures and accidents. Parag (2014), by his turn, mentions that the new environmental commitment of many nations to mitigate climate change adds many stresses to energy system. Thus, energy vulnerability can encompass all the political, social, economic, technical and ecological constraints.

For this reason, some authors prefer to limit the boundaries regarding energy vulnerability assessment. For example, Kruyt (2009) and Gnansounou (2008) related it to security of energy supply in a way that the more secure, the less vulnerable is a system or an area.

Beside the concept, it is necessary to define to which part of energy system the vulnerability is addressed. Regarding electricity, a shortage observed by a consumer may result of a default in generation, transmission or distribution system. However, as distribution comprises the largest infrastructure and so, it is more likely exposed to external perturbations, it is consequently more vulnerable than generation.

A few authors discuss and specify what could indicate vulnerability, i.e., empirical variables in the analysis of vulnerability. It is the case of Artigues (2008), who discusses vulnerability indicators to undertake a comparative analysis between European countries. According to the author, the first indicator is *diversity* of a system in a way that the more diverse the less vulnerable a system is. In other words, the more diversely supplied is an area, the less vulnerable it would be. Nonetheless, the assurance of energy supply does not account only for the diversity of sources, but also for an equitable use of this diversity.

Yet, diversity is useless if not all different sources are used equally to some extent. For example, if natural gas is available but underused it does not help to diminish energy vulnerability. Consequently, an equitable use of different energy sources would be a condition to diversity helps to diminish vulnerability. In the São Paulo context, for instance, natural gas is available in most areas, but it is incipiently used in a way that electrical energy keeps highly predominant.

The second indicator of vulnerability is *sustainability*, referring to the energy production and factors that may disturb it, as political instability and exhaustibility of sources. On the one hand, electricity, for instance, is more secure and stable in production, once it may come from several sources, but more vulnerable in distribution, as it involves a technically more complex grid and it is normally more exposed to external influences.

On the other hand, natural gas may be more vulnerable in the production, once is exhaustible and more affected by political issues (considering the Brazilian context where most gas supply relies on importation from Bolivia), but more secure in distribution. An evidence to that is the fact of electrical supply is more likely to outages than natural gas supply, although the production of the first is more durable in contexts where the vast majority of electricity is generated in hydroelectric power stations, as in Brazil.

Not only the exposure, but also the *sensitivity* to hazards is also important to define vulnerability. Sensitivity is "the degree to which the system is modified or affected by an internal or external disturbance" (Gallopin, 2006, pp.295). In this sense, it is vital to consider the context in which the system is, in order to evaluate its vulnerability. For instance: it is clear that the electrical grid is much more vulnerable than gas grid, because it is aerial in most cases, which means it is more exposed to perturbations.

However, it is not necessarily more sensitive just by being an overhead grid. The context could be a safe one, free from any kind of perturbations (heavy rains and winds, toppling trees, etc). In the context of São Paulo, electrical grid is vulnerable not only because it is overhead and, being so, more exposed to hazards, but also because hazards indeed exist, rising sensitivity. Furthermore, vulnerability rises due to inefficient maintenance of electrical grid and green cover (trimming trees services). Metaphorically, a person who is prone to get diseases would be more sensitive if surroundings are infected, and less sensitive if they are in a sterile neighborhood context.

Still, here we are not distinguishing these terms and we are considering them in a general way as *perturbations*. Turner et al. (2003) go a little further asserting that we have two kinds of perturbations: external and internal ones. A fault in the system would be an inside or internal perturbation, whilst a toppling tree or a gale would be an external or outside perturbation. Sources of stress could foment external or internal perturbation. For example, an internal perturbation could be caused by stress of the infrastructure getting obsolete at the same time that has to support more demand and pressure. On the other hand, an external perturbation could be fomented by a stress consisting in lack of prevention of falling trees due to faulty maintenance services.

Again, in this study we are not considering external or internal perturbation. Better still, we are considering that all perturbations are internal and should be treated accordingly. We justify this choice: being sensitive to perturbations (even caused by external facts) reveal the inability of the system of coping with them properly. Therefore, responsibility to higher or lower vulnerability is always an internal issue.

2. Materials and methods

We elaborate this map by applying ordinal chorochromatic with dasymetric base technique, through ArcGis software. The classes of vulnerability were defined by crossing five indicators through Analytic Hierarchy Process (AHP) proposed by Thomas Saaty (1990). It is a decision-making model in which all indicators involved have their weights stipulated according to odd numbers between 1 and 9, whose geometric mean and the percentage of each item generates a matrix with different weights, used as the mapping basis.

The AHP methodology allows changes in indicators and their weights. The proposal of using this methodology derives from the idea that each locality contains factors that can influence to a greater or smaller extent the interaction with the existing energy system.

In this sense, we drew the map based on Maliszewski and Perrings (2012), to whom the system presents its physical characteristics and the priorities previously established by the managers of the energy system.

The first approach that classified and localized areas with energy vulnerability was done by selecting five indicators for this case, as will be shown in the next section. We also delimited the study only to residential areas according to the land use map of the city of São Paulo, once the energy uses among the sectors (residential, commercial, industrial, transport) have great variations.

2.1. Indicators of energy vulnerability

1- *Dimension of the area served by only one substation.* Here, we took into account that, the more extensive is an area served by one electrical substation the more vulnerable it is. This occurs because in the case of outage, there is no other option around to recover supply.
2- *Availability of different or complementary source*. Based in Artigues (2008), the more diversified is the source of energy, the lower the vulnerability. Urban energy demand in São Paulo is typically provided by electrical energy with the participation of gas (natural gas and LPG) at least for cooking. According to the Balance of Energy of the Sao Paulo Estate of 2015, cooking represents 27% of energy demand in households, being the other 73% represented by all other uses that require energy (Ghisi et al., 2007). We considered this proportion 27% gas – 73% electricity) fixed to all areas, due to the lack of more precise data.
3- *Distance from main pathways.* According to Maliszewski and Perrings (2012), locations farther from arterial roads tend to have longer duration of power outages. The variable was obtained by distance from main traffic routes, calculated by São Paulo City Hall data. The closer to the avenues and other main pathways, the lower the energy vulnerability.
4- *Proximity to priority areas.* According to Maliszewski and Perrings (2012), houses that are closer to priority areas, such as hospitals and prisons, are likely to have their power restored much more quickly than houses farther away from these kinds of areas. Proximity to priority supply sites such as hospitals and prisons was calculated from São Paulo City Hall Data. The closer to priority sites, the lower the energy vulnerability.
5- *Density of trees* along pathways. We calculated the density of trees along and aside roads by census sector from São Paulo City Hall and IBGE[1] data. The lower the density of trees, the lower the energy vulnerability.

By applying the AHP methodology we found different weights for each indicator above (Table 1).

Having the matrix built (Table 1), we calculated the Consistency Index (CI), which is given by: $C.I = (\lambda max - n)/n - 1$; being λmax the higher number of Auto Vector, and "n" the number of analysed criteria. According to Saaty (2005), this calculation is important to know how consistent the opinions were. The lower

[1] Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics)

the result, the more consistent is the relationship between elements. To our study case, the CI was 2.8%, i.e., within the acceptable range, once results higher than 10% require a revision of the matrix [1].

We set four classes of vulnerability to each indicator, from low to very high (Table 2).

Table 1. AHP Matrix

AHP MATRIX	Dimension of the area served by substation	Availability of different source	Distance from main pathways	Proximity to priority areas	Density of trees	Auto Vector	Normalized
Dimension of the area served by substation	1	1	9	3	1	1.9	29.83%
Availability of different source	1	1	6	2	0.33	1.3	20.32%
Distance from main pathways	0.11	0.17	1	0.33	0.14	0.2	3.76%
Proximity to priority areas	0.33	0.5	3	1	0.33	0.7	10.74%
Density of trees	1	3	7	3	1	2.3	35.34%
Total						6.5	100.00%

Table 2. Classes of vulnerability

Vulnerability	Dimension of the area served by substation	Availability of different source	Distance from main pathways	Proximity to priority areas	Density of trees
Low *(Class 1)*	Between 25 and 502 hectares.	50% of the energy source composed by gas and served by piped structure.	Less than 50m from main pathways.	Distance up to 99m from hospitals and/or less than 500m from prisons.	Less than 3 trees per hectare.
Medium *(Class 2)*	Between 521 and 1,002 hectares.	50% of the energy source composed by gas, but without piped structure.	From 50m to 199m from main pathways.	Distance from 100m to 499m from hospitals and/or less than 999m from prisons.	From 3 to 6 trees per hectare

[1] We used the online software BPMSG, created by Klaus D. Goepel, to calculate the consistency index. <https://bpmsg.com/>

High *(Class 3)*	Between 1,024 and 1,691 hectares.	27% of the energy source composed by gas, served by piped gas.	From 200m to 499m from main pathways.	Distance from 500m to 999m from hospitals and prisons.	From 7 to 11 trees per hectare
Very High *(Class 4)*	Between 1,906 and 32,407 hectares.	27% of the energy source composed by gas, but without piped structure.	More than 500m from main pathways.	Distance bigger than 1000m from hospitals and prisons.	More than 11 trees per hectare.

3. Results and discussion

Based on this matrix, we mapped energy vulnerability to each census sector (IBGE) according to the formula shown:

$$V = [(I1\ x\ S1)w1] + [(I2\ x\ S2)w2] + [(I3\ x\ S3)w3] + [(I4\ x\ S4)w4] + [(I5\ x\ S5)w5]$$

Where:

V = Energy Vulnerability of the sector

I = Value of the indicator

S = Class of indicator (according to the tab le above)

W = Relative weight set by the AHP matrix, where $w1 + w2 + w3 + w4 + w5 = 1$

Firstly, we notice that the value of each indicator (for instance, X trees by hectare) was multiplied by its class (1, 2, 3 or 4), then, by its weight in the matrix. We repeated this procedure to each indicator and all results were added up to get the vulnerability class.

3.1. Results validation

In order to validate the map, we compared it with the indicators for quality of the power service from ANEEL[1] - DEC and FEC of consumer sets served by Eletropaulo.

DEC is the equivalent disruption duration (in Portuguese, *duração equivalente de interrupção*), and it expresses, in hours, the duration which the related area went out of power. FEC is the equivalent disruption frequency (in Portuguese, *frequência equivalente de interrupção*) and expresses the number of power disruptions faced by a certain area. The unit of area used by ANEEL is the consumer set that corresponds to the influence area of an electrical substation.

For each consumer set established by the concessionaire, its geographical limits were not provided, making it impossible to ascertain the exact amount of the participating census tracts for each set of consumers of Eletropaulo. However, as the Figure 2 evidences, the DEC-FEC has a clear visual correlation with vulnerability classes to the current context.

[1] Agência Nacional de Energia Elétrica (National Agency of Electrical Energy)

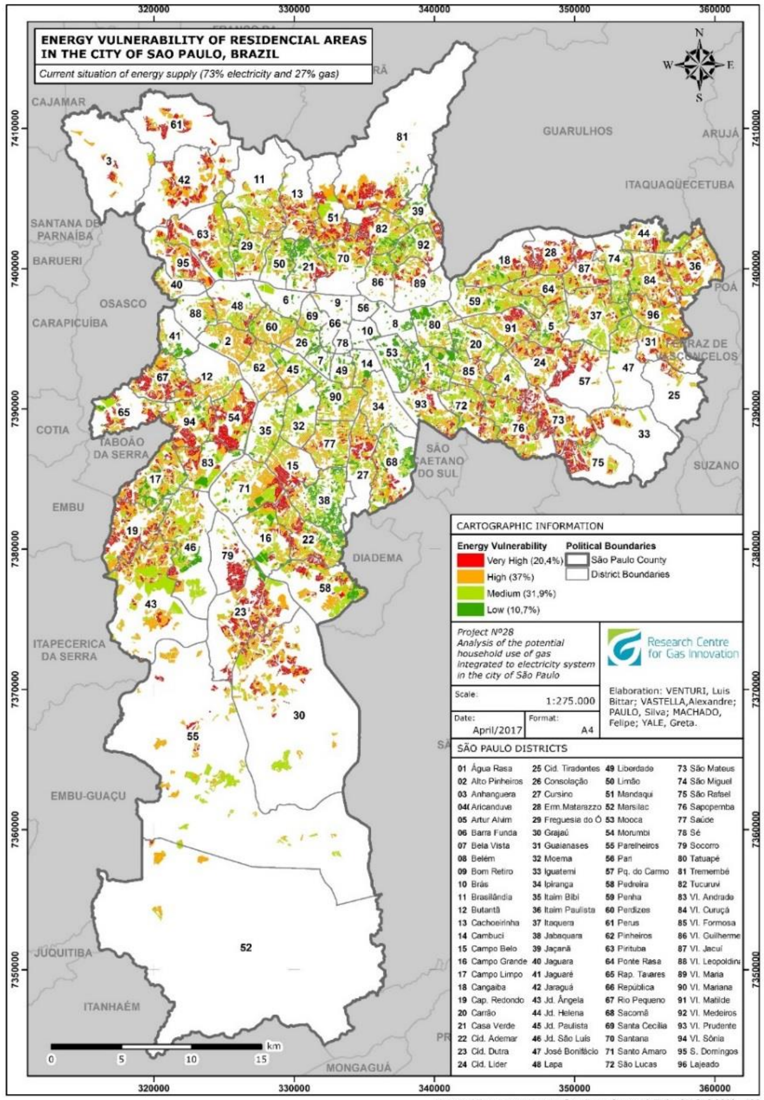

Figure 1. Map of energy vulnerability of the city of São Paulo (residential areas). Current situation

Given the lack of exact interpolation, we consulted areas in which the neighborhoods of the city and in which the Consumer Sets presented the same nomenclature to establish the connection.

While the *Bairro do Limão* presents a great variation of green tones in 2016, the *Limão* set consisted of a DEC of 16.6 hours and a FEC of 7.62 for 2016, while *Pinheiros* - mostly red, presented a DEC of 27.32 hours and FEC of 8.81.

The *Butantã* neighborhood, although containing areas from low to very high vulnerability, presented DEC of 25.69 and FEC of 8.81, of high average, above average for the region of the São Paulo.

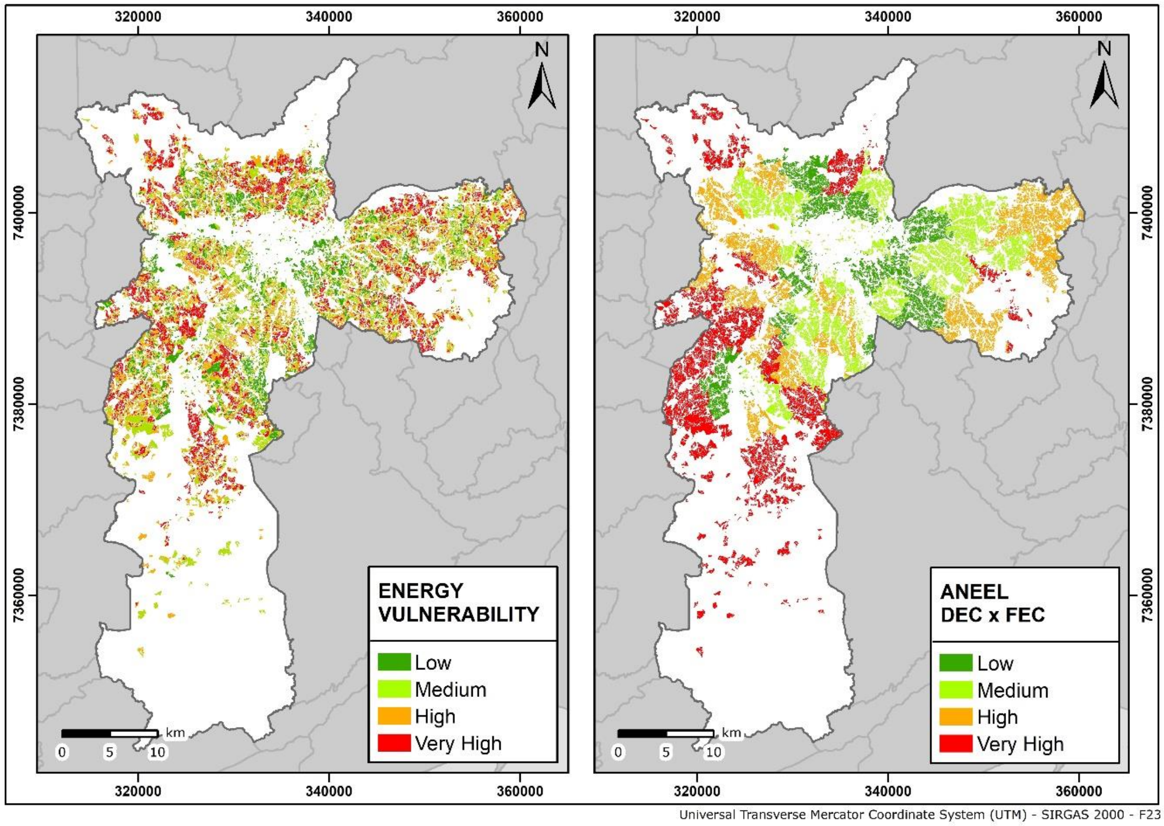

Figure 2. DEC-FEC and vulnerability classes visual correlation (current context)

3.2. Initial findings

At a first glance, we cannot identify a regular standard of vulnerability distribution. But analysing the map a little bit deeper, it reveals a tendency of an increasing vulnerability from the city centre towards periphery areas. Another finding refers to the fact that vulnerability is not directly related to social and economic level of the areas. We noticed high and very high vulnerability both in wealthy areas (such as *Alto de Pinheiros*, n.2, *Campo Belo*, n.15 and *Morumbi*, n.54) and areas with lower living standards (such as *São Mateus*, n.73 and *Ermelino Matarazzo*, n.28). In the case of wealthier areas, the high vulnerability may result from indicator 5, once those areas are traditionally more densely wooded. Another finding emerges when we observe contiguous districts with the same urban standard but showing contrast in energy vulnerability. This is the case of *Campo Limpo* (n.17) and *Capão Redondo* (n.19), being the last much more vulnerable than the first. It occurs as a result of the indicator 1, once *Capão Redondo* is a big area served by only one electrical substation.

On the other side, the proximity to many hospitals may account to the lower vulnerability of the *Avenida Paulista* region, comprising parts of the districts of *Bela Vista* (n.7), *Jardim Paulista* (n.45) and *Vila Mariana* (n.90), considering also the fact that those areas are crossed by a number of large avenues (indicator 3).

As a conclusion of this first map, we could assert that, due to the enormous heterogeneity and complexity of the city of São Paulo, both in terms of urban infrastructure, living standards, uneven availability of services (gas distribution, for instance), density of vegetation cover etc, it is not possible to define a predominant and regular standard of energy vulnerability. Each area has to be analysed according to its particular indicators combination, so that this map can be used to energy planning and management.

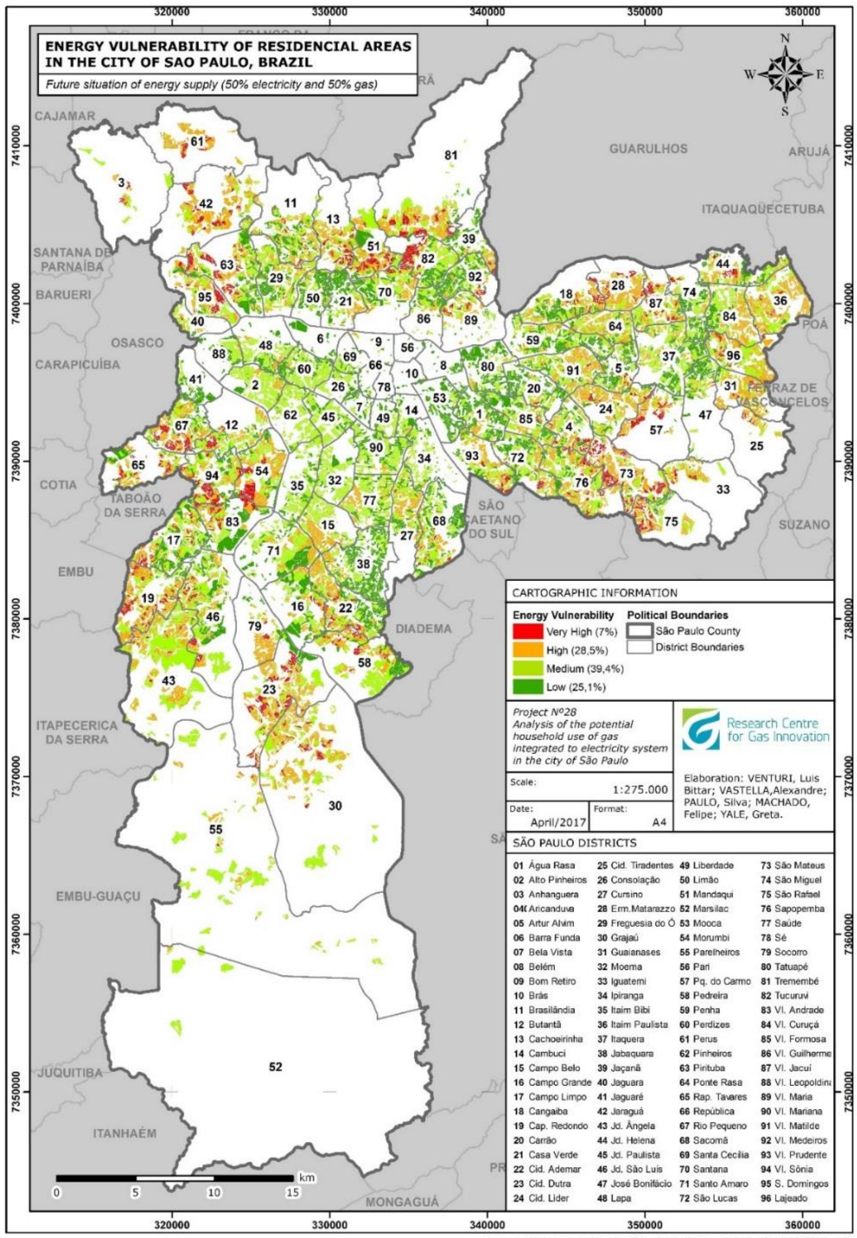

Figure 3. Map of energy vulnerability of the city of São Paulo (residential areas). Scenario situation.

3.3. Scenario of 50% gas - 50% electricity residential use

Here, we changed the proportion of 27%-73% for gas and electricity (indicator 2) rising the participation of the first. Doing so, we created a scenario equal use of gas and electricity by 50%-50%. The second map derived from this scenario showed significant changes in extension and distribution of areas of each vulnerability class.

Areas of *very high* vulnerability in the first map that represented 28.4% of all residential areas, dropped dramatically to 6.7%. In the same way, areas of *high* vulnerability felt from 27.8% to 15.3%. Areas of *medium* vulnerability felt from 25.8% to 23.7%. On the other side, *low* vulnerability jumped by 18% to 54.3%.

In general terms, we can assert that the vulnerability drop 11% in residential areas of the city of São Paulo, when we rise the use of gas from 27% to 50%.

4. Conclusion

We showed that this mapping methodology evidenced that by increasing the use of gas we could potentially diminish the residential energy vulnerability in the city of São Paulo, corroborating the hypothesis. This may be explained by two main reasons: it is due to the fact that having two options of energy supply turns residences less vulnerable once, in the lack of one source there is a second one. For instance, in a house supplied by electricity and gas, in the proportions of 50% each, in case of outage of electricity, at least half household functions keep on working. Secondly, because gas grid is always underground, which means it is less prone to perturbations due to weather conditions such as gales, storms, traffic accidents, toppling trees, etc.

Several other indicators could be included to frame vulnerability classes. Overhead grid, for instance, has different techniques of electricity distribution, being some safer than others. An area may be less vulnerable just by receiving electricity from several small power substations or being served by a high-tension grid and so on. All those technical variations were not considered in this first approach, though. However, as the map is flexible and can be modified at any time, we can add this new indicator (different types of electrical grid) to the matrix as soon as we get data concerning it or modify any indicator weight as the context changes.

Moreover, efficiency of maintenance services related to trees trimming or electrical grid maintenance itself could change significantly vulnerability classes. In conclusion, indicators are not fixed and may vary according to different contexts resulting in different vulnerability classes. It means that this kind of map is not permanent but dynamic and can be changed immediately by inserting new indicators or changing their weighs, according to the different contexts where it will be applied.

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