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Biogas Potential from Slums as a Sustainable and Resilient Route for Renewable Energy Diffusion in Urban Areas and Organic Waste Management in Vulnerable Communities in São Paulo

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Abstract: Slums are populated poor areas inside urban centers, mostly deprived of good-quality public services and exposed to inappropriate waste disposal and energy poverty. Using the organic fraction waste from these communities to generate high value-added products, including electricity, heat, and fertilizer, provides a circular bioeconomy with mitigation of greenhouse gas emissions, reducing environmental pollution and diseases. The present study aimed to demonstrate the feasibility of producing bioelectricity from the biogas obtained through the anaerobic digestion of the 400,000 tons of food waste generated in São Paulo's slums, the largest city in Latin America. The biogas potential was calculated using results obtained from previous studies, expanded to the slums, mapped, and discussed the environmental impact of waste mismanagement and the renewable energy source (RES) integration into the local energy system. The results show a bioelectricity potential of up to 147,734 MWh/y, representing 1.3% of the residential electricity demand with an associated potential reduction of 2111.7 CO_2eq Gg/y.

Keywords: renewable energy source; biogas; urban waste; bioelectricity; waste-to-energy

Citation: D'Aquino, C.A.; Pereira, B.A.; Sawatani, T.F.; de Moura, S.C.; Tagima, A.; Ferrarese, J.C.B.B.; Santos, S.C.; Sauer, I.L. Biogas Potential from Slums as a Sustainable and Resilient Route for Renewable Energy Diffusion in Urban Areas and Organic Waste Management in Vulnerable Communities in São Paulo. *Sustainability* **2022**, *14*, 7016. https://doi.org/10.3390/su14127016

Academic Editors: Zhengmao Li, Tianyang Zhao, Ke Peng, Jinyu Wang, Zao Tang and Sumedha Sharma

Received: 7 March 2022
Accepted: 30 May 2022
Published: 8 June 2022

1. Introduction

Slums are densely populated housing settlements without previous urbanization planning, usually associated with poverty. The houses are predominantly self-built and with a high degree of precariousness by low-income families in a situation of vulnerability [1]. As the emergence of the slums is associated with income concentration and unemployment in Brazil, the condition of vulnerability present in these communities is intrinsic to the UN concept of poverty [2,3]. Energy poverty is one of the manifestations of poverty, defined through the situation in which a house cannot meet the basic energy supply needs due to insufficient income [2].

Among the problems, the population faces living in these settlements include high rates of violence, deficient or absent water, sanitation, and electricity network services, low access to public transportation, low access to education, lack of cultural spaces and events, and fewer job opportunities opportunity. In addition, water and soil quality are affected by inappropriate disposal of waste at open dumping grounds, negatively impacting human health. Studies have shown that poor waste management is correlated with higher rates of diseases such as pneumonia, typhoid fever, lung infection, and bloody diarrhea. Also, dumpsites show a high concentration of heavy metals, like mercury, cadmium, arsenic, lead, and chromium, correlated with neurotoxic and carcinogenic effects [4].

Adequate waste management is based on the principles of sustainable development, considering its potential as a resource and its impact on public health [5]. Considering the high costs of waste collection and disposal, the destination of waste to energy production can reduce air, water, and land pollution and possible illnesses and deaths. Biogas is related to the best waste to energy (WtE) technology to treat the organic wastes from the available existing paths. It is a compact route and has various products range (biogas, electricity, biomethane, organic fertilizer), besides being carbon neutral [6].

The infrastructure for collection and disposal of the solid waste generated in the municipality, called Municipal Solid Waste (MSW), is especially lacking in areas such as slums due to its high costs for the local government [4,7]. A decentralized approach producing biogas from the Organic Fraction of Municipal Solid Waste (OFMSW) has been demonstrated as an affordable initiative to reduce costs and GHGs emissions, and to maximize both the integration of the produced energy into the regional matrix and the use of the end products, as the biofertilizer, for the local community [8]. Therefore, local community participation has been a positive factor in the project's affordability, requiring lower resources for operation and maintenance and encouraging source segregation, resulting in increased recycling [9,10].

The Brazilian electricity scenario faces the challenge of recovering its renewable mix while reducing costs and improving reliability in the face of recent episodes of high risk of shortages due to poor planning, deficiencies in the system's operation, and expansion capacity, combined with skyrocketing costs and tariffs. Brazil is uniquely endowed with renewable energy resources, mainly hydro, wind, solar, and biomass. However, over the last two decades, with the hiring of new capacity and the dispatch of the available capacity mix, thermal power has increased its share in supply, negatively impacting costs and emissions. Increasing non-dispatchable sources, like solar and wind, may expand renewable sources and reduce costs. However, the absence of storage structures reduces their contribution to the electric system. Biogas is a decentralized and flexible source that can be operated based on demand, allowing for dispatchable operation due to storage capacity, as herein proposed, can play a similar role in enhancing the value of PV solar resources [11].

Moreover, in vulnerable areas, such as slums, decentralized energy facilities, such as biogas and solar, can work as infrastructure hubs, reducing the local energy supply costs and as virtual power plants to the local energy grid [12]. So, energy mix diversification focused on the WTE perspective can be strategic to improve energy system reliability, enhance urban sustainability, reduce costs with waste management and energy distribution, promote access to sanitation, and improve communities' quality of life and health in vulnerable situations.

Additionally, the Brazilian electricity scenario faces the challenge of keeping its renewable matrix composition for the following years but mitigating the hydrological risk. The increase of non-dispatchable sources, like solar and wind, promises this clean expansion. Still, the absence of storage structures reduces their contribution to the electric system, resulting in the dependence of thermal power plants to meet demand with high-reliability levels [11].

So, the focus of this study is to (i) determine and map the biogas potential of the OFMSW in São Paulo's slums, (ii) estimate its bioelectricity potential, (iii) estimate the environmental impact of the waste mismanagement, and (iv) discuss the integration of this renewable energy source (RES) into the local energy matrix. Furthermore, the singularity and contribution of the present study are reasoned by the importance of demonstrating an applicable and practicable route on Brazilian slums, providing suitable waste disposal, better access to electricity using a RES, and, consequently, a reduction in the CO_2eq emissions and energy poverty present in these community.

1.1. Waste Management in the Municipality of São Paulo

In 2014, the São Paulo government launched the Integrated Solid Waste Management Plan for the City of São Paulo (PGIRS-SP), intending to improve solid waste management based on: non-generation, reduction, reuse, recycling, and correctly treating and disposal of solid waste. The plan includes the maximum waste segregation and its valuation and is applied to all public and private agents responsible for waste management.

The MSW collection and transportation is divided into two regions and is operated by two different private companies. The collected MSW is disposed of in the two operating landfills: East Waste Treatment Plan (CTL) landfill and the Environmental Treatment and Valorization Center (CTVA) Caieiras landfill [13,14], which receive daily 7000 and 10,625 tons of waste, respectively. Annually, São Paulo generates around 3.8 million tons of MSW, from which only 50 thousand goes to recycling. The remaining waste goes to landfill disposal and it is composed mainly by organic waste (49%), plastic (15%), paper and cardboard (11%) and diapers (11%) [15].

At the same time, the options for the correct destination of this waste are increasingly limited. Since the existing sanitary landfills are reaching their limit, both landfills must be closed until 2026, and there is no available land to construct new landfills. So, different approaches to waste management are important to be understood to face the new scenario. According to [16], an integrated waste solution for São Paulo city using the biological treatment of OFMSW to produce electricity and compost and a route to promote sorting technologies to recycle materials can reduce 70% of the material sent to landfills and impacts while promoting the highest social impact, compared with other options.

Currently, there are no large-scale biogas plants in the city of São Paulo. There is only the Experimental Unit in the urban area, located in the Institute of Energy and Environment, with an installed capacity of 75 kWe that can receive around 20 tons/day of kitchen and gardening waste. Nearby, all the large landfills use landfill gas to produce electricity. For example, Caieiras landfill has an installed capacity of 29.5 MW, located 40 km from São Paulo, and CTL landfill, of 5 MW, located 30 km from São Paulo. In the whole State of São Paulo, there are 60 operational biogas plants, 16 of them large-scale units and mostly from the sanitation sector (75%).

1.2. Electricity Consumption, Social Impact, and Biogas Relevance in the Context

Access to electricity can impact access to goods and services like education, food, heating, cooling, light, technology, and others, and it is considered in many ways a human right [17]. The main impact caused by the lack of access to electricity is the social inequality since only an adequate supply of energy can provide the conditions to eradicate poverty, improving the well-being of people in social and economic vulnerability [3]. The difference in energy consumption between countries is a great indicator of economic, cultural, and social development. Developed countries consume almost three times the world's annual per capita average of 85 GJ, while poor countries can present values 10 times lower than the global average [18]. The same differences can be seen on a regional scale, where families with high social vulnerability consume less energy and are in a condition of energy poverty. In contrast, families with social and economic privileges have better access to electricity. However, improving the electricity access to these communities results in higher electricity demand for the whole electric system, besides new investments in infrastructure to produce and distribute, which can impact the electricity cost to society, including low-income consumers.

Distributed Energy Systems (DESs), as micro-cogeneration and local energy hubs, can be advantageous in demand-side management [19]. In this case, biogas has a positive impact because of its flexibility and relatively cheap energy storage compared to other technologies. The latest studies have indicated that biogas in MSW-based biogas-solar-wind systems costs 22% less over the project's lifetime as they are less dependent on changes in fuel price due to locally available substrates [19]. In addition to these aspects, studies indicate that biogas also has a positive impact on CO_2 mitigation, the reduction of waste mismanagement, and the balance of stochastic energy production from intermittent renewable energy sources. Hybrid energy storage systems are more efficient and more economically attractive due to the possibility of interleaving between storage models, in which biogas can be used for long-term storage. At the same time, batteries can attend to short-term demand, resulting in maximum efficiency and an economically viable system [20–23]. Furthermore, the storage of compressed biogas in a biogas-solar-wind scheme can offset the energy fluctuations of different REs outputs and reduce the costs of battery energy storage [23]. Furthermore, the installation of biogas plants in these communities, as community-based microgrid (CBMG) or to inject electricity into the national grid, can also generate about 0.775–1.05 new local jobs per GWh, being one-third correlated to the development and implementation of the facilities, and two-thirds related to the operation [24].

This concept can have a particular impact on vulnerable communities, providing "immediate resilience" in the project, a higher domain, and a more secure return on investment [25]. According to the study by von Wirth, Gislason, and Seidl (2018), the success of a new renewable energy installation should consider not only the technical-economic feasibility but also the general approval, the local context, and the engagement of collective actors and individuals, to promote a connection between the community need and the technology solutions [19]. So, biogas-based DES can be a local solution for waste management, energy access, and CO_2 mitigation, with the proper engagement of multiple stakeholders, with economic and social impacts, such as job generation and postponement of investments in the electric energy distribution and transmission sectors, focusing on technical quality, economic viability, and social ethic.

2. Materials and Methods

2.1. Research Design

Departing from its purpose, this study combines quantitative and qualitative approaches to provide the mapped potential of bioenergy from biogas in São Paulo's slums, divided into districts, based on the extrapolation of results obtained by [26]. First, quantitative data was used to determine and analyze (i) the location and geographic distribution of the inhabitants living in slums per district, (ii) the generation and geographic distribution of OFWSM in the slums and its bioenergy potential, considering the biogas production, and (iii) the environmental impact of using biogas to treat OFMSW, in terms of mitigation of CO_2 emissions. Further, qualitative data were used to discuss (i) the relevance of the community engagement to this technology and (ii) the impact on the local energy system. So, this study aims to describe some of the impacts of implementing community-based renewable energy systems as a resilient option to insert biogas into urban areas and improve access to energy, jobs, and food in these areas.

2.2. Study Area and Estimation of the Population Living in Slums

With an extension of 1521.11 km^2, São Paulo is the most populous city in Brazil, the largest city in Latin America, and one of the largest cities in the world. It is located at 23°32′56″ S latitude and 46°38′20″ W longitude. The richest city in Latin America, São Paulo, has a Gross Domestic Product (GDP) of US$ 123 billion (US Dollar to Brazilian Real Exchange value from March 2021 (1 USD = 5.77 BRL)) [27], is responsible for 10.2% of the Brazilian GDP, and has the 18° biggest GDP in the world [28]. Despite having a per capita GDP of US$10,166.27 [27], the city also shows alarming indicators of social inequality, with a solid regional correlation. There is a difference of 3.5 times between the monthly income of the poorest district and the richest one, 12 times in the access to childcare, and 18 times in school dropout [29].

The data used to map the population living in slums were obtained from the housing census applied by the Municipal Council. Results showed an average of 9.5% of the city's households in slums, and this percentage ranges from 0% of the households in slums—in the richest districts—to 68.8% of peccary households—in the poorest one [29].

2.3. Organic Waste Generation and Environmental Impact

The Organic Fraction of the Municipal Solid Waste (OFMSW) produced in these areas was calculated using the parameters shown in Table 1.

Table 1. Parameters used to estimate the Organic Fraction of the Municipal Solid Waste (OFMSW) and biofertilizer production in São Paulo's slums.

Parameters	Value	Unit	Reference
Waste generation rate	1.7	kgMSW/inhabitant.d	[14]
Organic content	49	%vol	[15]

The total organic waste generated in these locations is calculated using Equation (1), where Pop_{slum} is the total population living in slums and Q_w is the waste generation rate:

$$OFMSW = Pop_{slum} \times \frac{(Q_w \times 365)}{1000} \times 0.49 \quad (1)$$

To calculate the mismanaged OFMSW, the waste collection rate per subdistrict is applied. The city is divided into a total of 96 districts and 32 subdistricts. The subdistricts are responsible for waste management, and the total waste collected per subdistrict ranges from 0.19 t/y.inhabitant to 0.61 t/y.inhabitant. With a waste collection rate of 3.2 higher, the richest areas are less impacted by waste dumping, reducing soil, air, and water contamination, and disseminating disease-carrying pests. The total waste generation discounted the waste collection is considered the mismanaged OFMSW.

The Global Warming Potential (GWP) of the MSW mismanagement was calculated according to Equation (2) [5].

$$CO_{2eq} = (OFMSW \times EF_{CO2}) + (OFMSW \times EF_{CH4} \times GWP_{CH4}) \quad (2)$$

where OFMSW is the Organic Fraction of the Municipal Solid Waste (Gg/y); EF_{CO2} is the emission factor for carbon dioxide (2.25 Gg/Gg), EF_{CH4} is the emission factor for methane, which is equal to 0.097 Gg/Gg, or the average between the reported values to São Paulo's landfills [30], and GWP_{CH4} (Global Warming Potential), is 25 for CH_4 [31].

2.4. Bioelectricity Potential Assessment

Combined heat and power engines (CHP) with an electrical efficiency of 40% were considered to convert biogas into electricity [32]. Assuming 9.97 kWh/Nm^3 as the lower calorific value of methane and the biogas production potential per ton of substrate, the electric energy potential may be calculated by Equation (3).

$$E_E = V_{CH4} \times Re_{CH4} \times \eta_e \quad (3)$$

E_E represents the electricity generation, in kW/y; V_{CH4}, the volume of produced methane, 113.79 $Nm^3/t_{substrate}$ [26]; Re_{CH4} as the lower calorific value of methane; η_e represents the CHP electrical efficiency. The installed capacity (IC) can be determined from Equation (4), considering 7884 as the system's operating hours in a year (capacity factor of 90%).

$$IC = \frac{E_E}{7884} \quad (4)$$

3. Results and Discussion

3.1. Population in Slums, Organic Waste Generation, and Carbon Emissions

The results show that in 85 of the 96 districts of São Paulo, there are inhabitants in the slums. According to the municipal council, the average number of occupants per household is 3.49. Therefore, of the total population of 11,253,503 people [33], around 1,198,451 live in this precarious type of housing. In 11 districts, slums represent more than

20% of the total household. In the districts of Jardim Angela and Jardim São Luís more than 50% of the population live in the slums, 53.27% and 68.8%, respectively. On the other hand, only 10 of the 96 districts have no households in slums, with a total population of 777,158 inhabitants [1,29].

Considering the waste generation rate and its organic content, it is estimated to be a generation of 435,016.6 t/y of OFMSW in all of São Paulo's slums, being 55.8% located in the 11 districts where more than 20% of the population live in slums (Table 2). Applying the collection rate per district [29], a total of 1.7 t/y of OFMSW mismanaged in the city was estimated. From this, around 21% are generated in the 11 districts, with more than 20% of the inhabitants in slums, where the average waste collection rate is 0.3 t/inhabitant.y, which is 9 times higher than the districts with no inhabitants in slums, where the average waste collection rate is 0.54 t/inhabitant.y, as shown in Table 2.

Table 2. Results from the population in slums, waste generation and management, and emissions.

<table>
<tr><th>Parameter</th><th>11 Districts >20% Inhabitants in Slums</th><th>10 Districts with no Inhabitants in Slums</th><th>Slums Total</th><th>City Total</th></tr>
<tr><td>Total population</td><td>2,354,117</td><td>683,891</td><td rowspan="2">1,430,764</td><td rowspan="2">11,869,350</td></tr>
<tr><td>Population in Slums</td><td>799,245</td><td>0</td></tr>
<tr><td>Total OFMSW generation (t/y)</td><td>715,757</td><td>207,933.6</td><td rowspan="2">435,016</td><td>3,608,816.5</td></tr>
<tr><td>OFMSW generation in slums (t/y)</td><td>243,006</td><td>0</td><td>435,016.6</td></tr>
<tr><td>Mismanaged OFMSW (t/y)</td><td>361,882</td><td>39,479</td><td rowspan="2">222,959</td><td>1,738,238</td></tr>
<tr><td>Mismanaged OFMSW in slums (t/y)</td><td>125,807</td><td>0</td><td>222,959</td></tr>
<tr><td>Average waste collection rate (t/inhabitant.y)</td><td>0.30</td><td>0.53</td><td>-</td><td>0.35</td></tr>
<tr><td>Total CO_{2eq} emissions from mismanaged OFMSW (Gg/y)</td><td>574.4</td><td>47.96</td><td>1012.8</td><td>2111.7</td></tr>
</table>

MSW is a significant source of anthropogenic greenhouse gases (GHG), contributing to between 3–9% of global emissions [5,34]. The MSW generated is continuously increasing in developing economies. For example, in Brazil, it was observed an increase of about 0.89% in the MSW generated between 2019 and 2020 when the population increase was 0.77% [35,36]. With deficient coverage in waste collection and treatment, the increase in waste generation tends to increase the exposure of vulnerable communities to waste disposal. With an average generation of 0.62 t/waste.inhabitant.y, only 8 districts have a collection rate of 98% (0.61 t/inhabitant.y), while 42% of the districts have less than 50% of waste collection coverage. With a total average rate of 0.35 t/inhabitant.y, about 1.7 million tons of OFMSW may be mismanaged, which means an annual emission of 2,111.7 Gg/y, of which 48% are from the population living in slums. Considering an average of 8% of households in this condition, these communities are disproportionately exposed to poor waste management.

The emissions from OFMSW conversion into biogas depend on many factors, such as the application of the digestate and the assumptions related to gas and liquid leaking. The literature reports values between 0.96 and 20.04 $kgCO_{2eq}/t_{food\ waste}$ [37,38] in many different scenarios, which could represent a reduction of 99% in the carbon emissions. So, the management of the OFMSW using the biogas technology could result in emissions between 0.3 and 7.1 $GgCO_{2eq}$/year.

3.2. Bioelectricity Potential in Slums and Its Integration into the Local Energy Matrix

The total bioelectricity potential from the OFMSW generated in the slums in São Paulo city is 147,733.9 MWh/y, which means an installed capacity of 18 MW_{ave}. From the total, 90,875.2 MWh/y are in the 11 districts with more slums, distributed according to Figure 1.

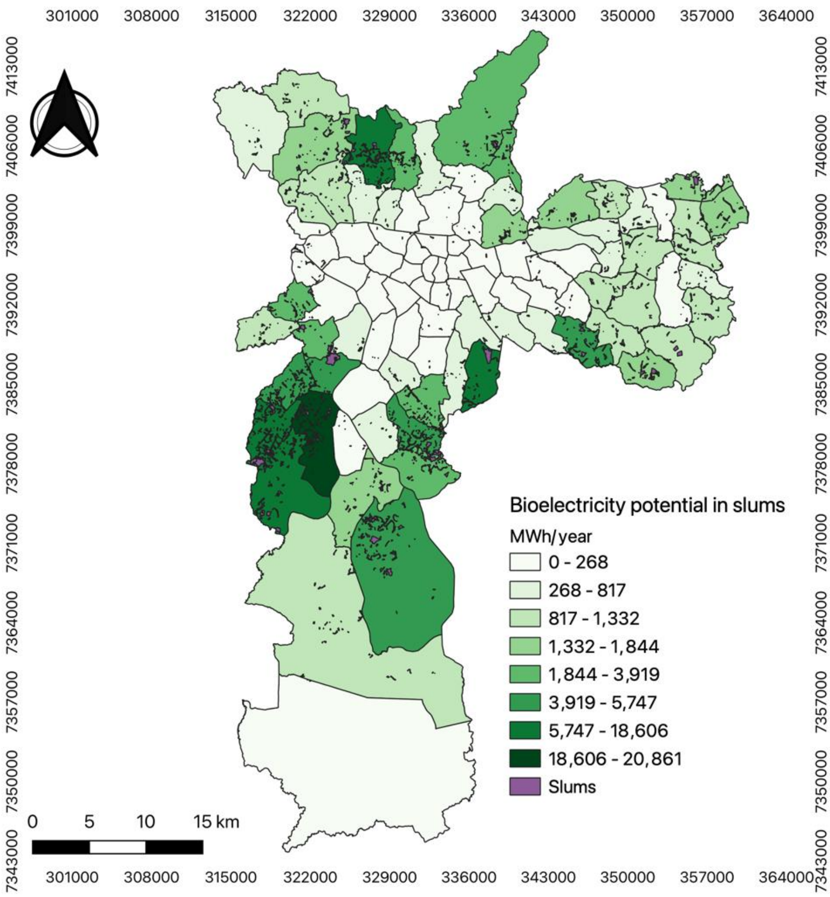

Figure 1. Bioelectricity potential from OFMSW in São Paulo's slums.

According to studies [39], 99% of the electricity consumed in São Paulo is imported, putting the city in a high-risk environment in terms of prices and supply. Considering an electricity consumption of 27,512 GWh in 2019 [40] (Figure 2), the bioelectricity potential calculated in this study represents 1.3% of the residential demand, 15% of the government demand, or, an increase of 5 times the current distributed electricity production.

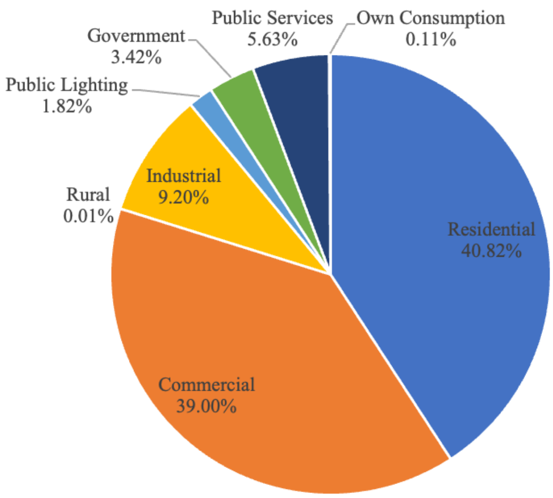

Figure 2. Share of electricity consumption of São Paulo, according to consumer class [40].

Therefore, biogas application as a decentralized energy source can improve the supply/demand balance as a flexible multi-energy source in the integrated energy system. With a high local impact, this DES concept is a socio-technical system for sustainable transition integrated with social responsibility [41], which can be the more cost-efficient, environmentally friendly, and energy-efficient use of biogas [23]. The communities' engagement is also a key factor, since developing countries face difficulties providing technical knowledge and low-quality digesters, resulting in failure [42]. At the same time, the route has the energetic and environmental value for these communities and a material value, since nutrients from digestate can be applied as fertilizer and soil conditioner. In this sense, a buyback program as a viable method to improve community engagement, create jobs and change the value proposition of these systems [43].

Other important product of the biogas chain is the digestate, considered as a suitable biofertilizer that can replace the mineral fertilizer, improving the soil fertility, and vegetable production yield [44]. Each ton of food waste can generate 0.09 tons of dry biofertilizer [26,45], which means a potential of 20,066 tons of biofertilizer that could be used to produce food in urban areas, which impacts positively on food security, biodiversity, climate change and public healthy [46].

There are several configurations to implement and operate these systems, and some factors such as technical knowledge and infrastructure are primordial to define the best option. Implementing several digesters in the city can be a challenge regarding available operators, investment, and logistics. CBMG is an emergent area, but still rare, and there is only one known CBMG biogas-based, located in Germany [47], being solar and wind the most common technologies applied.

Implementing fewer facilities that concentrate the waste generated in a specific perimeter can be a reliable strategy. However, the economies of scale in biogas highlight the importance of substrate transportation in the plant operational and the plant's environmental impact, once longer distances represent a higher impact on emissions [48,49]. Therefore, to increase the profitability of a biogas plant, it is essential to maximize the transportation of the substrate from its origin to the facility, which depends on the substrate density, vehicle type, and distance is the maximum displacement distance between 15 and 25 km [50].

4. Conclusions

The social and health problems faced by the communities that live in slums are evident. São Paulo is the largest city in Latin America, and a multi-approach view over the water-food-energy should take place, especially for those in a high-vulnerable situation. This study demonstrated biogas as this multi-approach tool to improve waste management, reduce emissions, and produce high-quality bioelectricity.

Giving the right destination to the organic residues generated in São Paulo's slums to biogas facilities could reduce 2111.7 Gg/y of CO_{2eq} and produce 147,733.6 MWh/y of bioelectricity, 6% of the total energy consumed in the city in 2019. This energy can also minimize the current dependence on imported energy, reducing the cost to all consumers.

Future studies could be applied to other categories of waste generators or even the whole city, including relevant data on costs to implement these systems. This study aims to discuss the importance of a better look into the community that is mainly suffering from waste mismanaging and, often, low-quality energy, besides the direct consequences of the state of energy poverty present in these community. However, the whole society can benefit from the services and products delivered by the biogas technology.

Author Contributions: C.A.D. Conceptualization, writing—original draft, and supervision B.A.P. Data curation, investigation, methodology T.F.S. Data curation, investigation, methodology S.C.d.M. Writing A.T. Formal analysis and investigation J.C.B.B.F. Formal analysis, investigation, and administration S.C.S. review and supervision I.L.S. Conceptualization, Project administration, supervision, validation, writing and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: National Electric Energy Agency (ANEEL): Project number 00390-1086/2018 (ENEL)—Integrated assessment of distributed generation, demand management, monitoring, quality, and performance of the network, aiming at optimizing investments and tariff regulation in the underground network, and Project number 00061-0054/2016 (CESP)—Analysis of the efficiency of complementary energy storage with hydroelectric plants, using electrochemical and hydrogen storage technologies.

Acknowledgments: The authors would like to acknowledge the financial, technical and institutional support continuously received from the Institute of Energy and Environment of the University of São Paulo (IEE-USP).

Conflicts of Interest: The authors declare no conflict of interest.

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