Comparison of externalities of biogas and photovoltaic solar energy for energy planning

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Highlights

- The externalities of biogas and photovoltaic systems were economically evaluated
- Are externalities worth more than energy generated by biogas or photovoltaic systems?
- The externalities assessment show that biogas should be prioritized over PV system
- Government incentives are needed to promote biogas in Brazil
- Organic waste is an important source of opportunities in the energy sector

Abstract

The Brazilian electricity matrix is around 80% renewable and it has registered continuous growth in the expansion of biogas and photovoltaic (PV) systems. The main current Brazilian incentive program for the distributed generation of renewable energy, through a single net metering tariff, that is, a generation compensation system in credits to the consumer who owns the generating unit, does not seem to be effective to promote the expected growth of the biogas. Thus, the objective of this paper was to evaluate quantitatively and qualitatively a set of significant externalities for both sources to contribute to a more realistic energy planning. The externalities quantitatively evaluated for these two renewable sources were: avoided emissions, employment and income, biofertilizers for biogas and use as a constructive element for PV systems. A significant result was that the economic value of the externalities of biogas can exceed those of PV systems for the rural producer by more than 11 times, for society by 1.7 times. It is concluded that, due to the value of biogas externalities being much higher economically than those of PV systems, Brazilian public policies for energy planning should prioritize biogas over solar photovoltaic energy systems.

Keywords: Renewable energy; public policies; indirect impacts; avoided emissions; quality of life.

1. Introduction

With the growing environmental concern, renewable energy sources have become a priority in energy planning worldwide. Many studies, in the past, sought to evaluate development indicators only related to economic growth and energy consumption. However, the tendency is to look for a multivariate set of indicators that primarily integrate the emission of pollutants (Hdom, 2019). The use of energy sources is essential in the climate change debate and energy planning, where “green electricity” has become a promising approach to climate change mitigation (Kaiser et al., 2020).

Brazil has a predominantly renewable electricity matrix, about 80% of the energy consumed in 2022 came from such sources (MME, 2022). Even though it is already an example for the world of the participation of renewable sources in the electricity matrix, Brazil also needs to continue to evolve, given global goals for the continuous reduction of dependence on fossil sources. Especially, photovoltaic (PV) solar energy systems stands out as a generation alternative that has been massively implemented in the country, especially in the last 10 years. The consolidation of PV systems in Brazil took place mainly after the regulation of micro and mini energy generation in the country, which only occurred, belatedly, in 2012 (ANEEL, 2012). Since the 1990s, Japan and Germany have become leaders in the development of photovoltaic energy sources, catching up with the US, which initiated the consolidation of the energy source, mainly due to government incentive programs (Wen et al., 2020).

Another prominent renewable source in the Brazilian energy matrix is biogas, especially when derived from waste. Brazil has great potential for biogas production, given its extensive agricultural production, agribusiness and urban solid waste and consequent volume of organic waste generated (Cruz et al., 2021). Biogas began in the 1980s in Brazil, despite being an already known energy source and expanding, it is still little explored. It should be noted that currently the consumption of natural gas represents 26 times the current production of biogas (Sinigaglia et al., 2022). As a substitute for natural gas, whether purified in the form of biomethane, biogas demands great attention in Brazilian energy planning, given that the country's production potential is among the largest in the world (Abiogás, 2023; Sinigaglia et al., 2022).

Brazilian public policies that govern distributed generation systems for renewable electricity are based on rate that only allow compensation for consumption, i.e., net metering, for generating plants of up to 10 MW of installed capacity. This current compensation system is valid for both biogas sources and PV systems (Brasil, 2022). Another possibility for biogas producers is the direct sale of this energy source, certified by the RenovaBio governamental program. The program allows the biogas producer to receive carbon credits, called C_{Bios} (Brasil, 2017). It should be noted that the RenovaBio program was proposed in 2016, but it was only implemented in 2020.

The generation of electricity through biogas in Brazil is still little explored, in 2021 it reached 228 MW of installed capacity and has accumulated an average growth of about 11% per year since 2012. On the other hand the distribution generation, DG, from PV systems reached an installed capacity of 4632 MW in the same period with an average growth of about 117% per year in the same period (MME, 2022). In other words, power generation plants via biogas in Brazil have an installed capacity around 20 times lower than the PV and an average annual growth around 10 times lower. This demonstrates the need to improve Brazilian public policies in this sector.

On the other hand, it is notable that the installation of PV systems presents more facilitators, since to generate biogas, it is necessary to have available organic materials to be biodigested. The lower growth of biogas can be attributed to the negative experiences rural producers had in the 1980s and the low economic attractiveness. The difficulties, which still persist for more than 40 years, are primarily associated with the difficulty in operating the biodigesters and the lack of technical knowledge (Sinigaglia et al., 2022; Sousa et al., 2020). If significant changes occur in Brazilian regulations, it may increase the attractiveness for new biogas production projects.

The production of biogas by anaerobic digestion of residues is widely recognized as the opportune technology to aggregate the reduction of environmental impact and produce organic by-products of economic interest. This alternative for treating organic waste has been recognized as a powerful way of producing biogas and simultaneously reducing the emission of greenhouse gases (Achinas and Euverink, 2020; Neshat et al., 2017). Composting has the advantage of being able to produce high quality solid biofertilizers, in comparison, anaerobic digestion allows the production of biogas, does not require oxygen, mitigates the emission of pollutants and water vapor into the atmosphere during the process (Dadrasnia et al. , 2021). That is, the production of biogas via anaerobic digestion has several advantages or positive externalities, which must be evaluated.

Externalities, in general, are defined as external impacts arising from a given activity, which can be quantified physically and economically (Martinez-Sanchez et al., 2015). According to Jensen and Skovsgaard (2017) the definition refers to the positive or negative impacts caused in the external environment. The production of biogas through anaerobic digestion to generate electricity and the generation of solar PV electricity are activities that significantly impact the environment. These impacts are called in this study externalities of biogas and PV systems.

The externalities of biogas and PV systems tend to be positive, in most cases, and are widely recognized as advantages of these renewable sources (Bartczak et al., 2017). The positive externalities of renewable energy sources, although recognized, are mostly not quantified or directly internalized in economic analyses, many times (Wang et al., 2016). Only the tacit recognition, without the explicit economic internalization, of the externalities of PV systems can already be enough as a probable explanation for the great development that this source has presented in the last years in Brazil.

In most cases, among the positive externalities of biogas, one can mention the improvement of sanitation, reduction of environmental impacts, possibility of producing biofertilizers, among others (Manesh et al., 2020). Despite being recognized by several researchers, the externalities of biogas are little studied (Nordahl et al. 2020). The internalization of externalities in economic evaluations can be fundamental in the process of prioritizing the energy planning of electricity generation using biogas over other possible sources.

What is expected is that externalities are integrated into the analyzes so that renewable energy planners have the correct economic dimension and external impacts involved. Furthermore, the understanding of externalities can be evaluated from different perspectives, in addition to that of consumers, the power plant, as well as society (Sovacool et al., 2021). Comprehending the benefits of renewable energy in a broad and particular way for each source enables specific targeting, through energy planning, of incentives for each renewable source, maximizing those that are more strategic in each particular case.

The importance of incentive policies for biogas was evaluated in several studies, which proved their need for the development of biogas production (Luo et al., 2021). Government incentive policies should aim not only at implementing new energy generating units using biogas, but also at maintaining existing ones. This need is evident from the high rate of abandoned projects, including in Europe, which reaches around 30% (Bourdin and Nadou et al., 2020). In China, there was also an implementation incentive program that achieved great adherence, however, it failed to keep the plants in operation (Wang et al., 2016). As for PV systems, what can be seen is that the current Brazilian policy is allowing for significant growth, but as it is recent, it may need to be reassessed in the future to allow this energy source to continue to grow.

Externalities can contribute as a decision factor to incentives directed at certain renewables. What is expected is that a greater understanding of externalities can help to guide public policies, economically prioritizing accordingly. The priority may be related precisely to the renewable source of electricity generation that provides more valuable externalities to society, thus justifying the funding of government incentives. Thus, it is concluded that a greater understanding of the externalities of biogas and PV systems can help in energy planning and, consequently, in the full development of both sources.

That is, to compare the externalities of renewable sources of electric power generation can allow a more accurate energy planning, providing a better understanding of each source, but respecting the priorities, and by doing so the planning will be in a most fair way. Thus, the present paper aimed to comparatively evaluate the externalities of two renewable sources of electricity generation by burning biogas and by PV systems in rural properties as a way to contribute to energy planning. The results obtained are expected to be used in the development of public policies to encourage renewable energy.

2. Methodology

The externalities of distributed generation of electricity were evaluated quantitatively and qualitatively, through the production and burning of biogas from organic swine waste and through solar PV systems. The externalities involving energy generation for these two sources were called biogas and PV system externalities, respectively. Three perspectives were studied regarding the distributed generation: society, the energy utility and the prosumer. Where in this study the prosumer means an rural producer that at same time is an energy producer and a consumer (Hua et al. 2022).

The production of biogas from swine farming waste was considered in rural properties with medium to large-scale size, i.e. with an electricity generation capacity greater than 100 kW (Oconnor et al., 2021). Representative data for Brazil, specifically for Minas Gerais, was used. The state was selected because it is the fourth largest producer of swine meat and the third largest from an economic point of view. It is also noteworthy that annual solar radiation reaches values greater than 2.0 MWh/m^2 in most of the state (Martins et al., 2012). It was considered for biogas that the efficiency of electric power generation systems and methane concentration allow, on average, the generation of 2.2 kWh/m^3 of biogas (Indrawan et al., 2018; Budzianowski, 2016) .

Table 1 presents a summary of the externalities studied for the generation of electricity from biogas of agricultural waste and for photovoltaic solar generation, which were evaluated from the perspectives of society, rural prosumers and the electricity utilities.

(Table 01)

2.1. Avoided emissions

The avoided emissions externality was estimated using the methodology for quantifying avoided emissions in the process of generating electricity by burning biogas and for PV systems, both connected to the grid in the form of distributed generation of electricity. For the generation of electric energy to biogas, it was considered the production of this by means of anaerobic digestion of swine farming residues. For PV systems, installation on the rural property was assumed.

The externality in question was evaluated from two perspectives due to the financial opportunity of avoided emissions for prosumers and the impacts of pollutant emissions on society in general. From the perspective of the prosumer, it was possible to estimate the economic value of this externality based on the quotation of carbon credits in the Brazilian market, C_{bio} and the European Union Emissions Trading System (EU_{ETS})”. (B3, 2023; ICAP, 2023). From the perspective of society, it can be calculated in terms of the social cost of carbon

(S_{CC}), which is defined as the amount of damage from the impacts of climate change associated with an additional ton of $CO_{2\ eq}$ emitted to the atmosphere (Isacs et al., 2016).

For the generation of electricity using biogas, three factors were considered: (i) Avoided emissions in contrast to composting; (ii) Emissions from the burning of biogas to generate electricity were neglected, considering the production of biogas from waste, which implies that emissions have already been previously offset, due to the carbon sequestration that occurred in the plant production stage; (iii) Avoided emissions considering the current Brazilian electricity matrix, that is the country generation mix (Sardá et al., 2020; Dutoit et al., 2014; Sardá et al., 2018; Oliveira, 2001; Burg et al., 2018).

Avoided emissions for generating electricity by producing and burning biogas were quantified in terms of tons of $CO_{2\ eq}$ due to the mitigation of the global warming potential of CH_4 and N_2O (IPCC, 2013). For emissions from biogas burning, complete combustion was considered, with CH_4 converted into CO_2 and H_2O; and N_2O into N_2 and O_2. For the current emissions equivalent of the Brazilian electricity matrix, data from the national energy balance of 2022 were considered (MME, 2022).

In the case of rural properties with PV systems, the avoided emissions of $CO_{2\ eq}$ to generate electricity were estimated, as well, considering the current emissions of the Brazilian matrix, as was done for biogas (MME, 2022).

2.2. Employment and income

To estimate the economic value of the employment and income externality, the opportunity to create jobs and income from the generation of electricity through biogas and PV systems were considered. It was determined, through a literature review, the labor costs for installation and maintenance of electric power generation plants using these two sources. These costs were normalized and apportioned over the useful life of the generation systems, obtaining a levelized cost of electricity (L_{COE}) in US$/kWh.

The labor cost for installing energy generation systems using biogas and PV systems were considered equal to 20% of the total L_{COE} for the first source and 35% for the second source (Oliveira et al. 2021; Nogueira et al., 2015; Iglesias and Vilaça, 2022). The estimate of the value of the employment and income externality for each of these generation sources were estimated by the percentage of the average values of the L_{COE} corresponding to the cost of labor for installing the energy generation systems, as shown in Table 2.

2.3. Peculiar externalities of each renewable source of generation

An externality peculiar to biogas was evaluated, which is the use of biofertilizers from the effluent, and another peculiar to PV generation, which is the use of PV panels as building material. This was due to the need to clearly differentiate between the two renewable energy sources. A particular methodology was developed to assess each of these externalities.

The use of biofertilizers` externality was estimated for biogas considering that the generation of electricity in this situation generates effluent as by-product, with the capacity to be a source of biofertilizers. The concentration of NPK (Nitrogen (N) Phosphorus (P) Potassium (K)) can be variable, so we considered the compositions of the swine digestate according to Lukehurst et al. (2010) and Cândido et al. (2022). Considering the costs of fertilizers that make up the commercial NPK in Brazil and using the conversions of these compounds, it was possible to evaluate the economic value of this externality by the macronutrients produced as a function of the amount of biogas produced (MAPA, 2022; MME, 2001).

The externality of using PV panels as a building material was estimated for PV systems, considering that they can be installed as roofing element in rural buildings, reducing costs with tiles and support structures. Thus, using the methodology proposed by Castro et al. (2022) it was possible to calculate the value of this externality. The possibility of replacing fiber cement and galvanized tiles that are commonly used in swine farming was considered (Mós et al., 2020). The methodology allows estimating this externality considering the average cost of roof tiles, support structures and PV modules, yields and efficiencies of PV systems, solar radiation and system operating period (Ekici and Kopru, 2017; CANADIANSOLAR, 2023).

2.4. Qualitative assessment of externalities

The power quality externality was qualitatively evaluated from the perspective of the electricity utility, considering the sub-externalities: (i) avoided electrical losses in distribution; (ii) improvement of voltage profile; (iii) improvement of systems reliability. From the utility perspective the following externalities were also evaluated: postponement of investment in transmission and distribution and energy storage.

From the perspective of the rural prosumer the following externalities were evaluated qualitatively: (i) energy storage, considering the losses of non-supply of energy and the greater reliability resulting from energy storage; (ii) modularity, flexibility that the prosumer has with systems that can be implemented in different generation capacities and with easy expansion of the installed capacity; (iii) cogeneration, allowing the simultaneous use of thermal and electrical energy.

From the perspective of society, the improvement in quality of life provided by environmental conditions due to the reduction of pollutant emissions was evaluated. This assessment was based on indicators cited in scientific papers that allow estimating the relationship between quality of life and environmental factors.

3. Results and discussion

The results obtained were related to data that best represent the reality observed in Brazil, which were the basis of the evaluation to estimate the economic value of externalities. The economic value of the four quantitatively evaluated externalities ranged from 0.0004 to 0.1602 US$/kWh, depending on the externality and evaluation perspective. Six externalities were also qualitatively assessed. Technical and economic aspects of externalities reinforce the importance of internalizing these results in economic analyzes and energy planning.

It is worth mentioning that some of the evaluations presented were made based on the installed power parameter of the two renewable energy sources of systems connected to the grid, i.e. biogas and PV systems. But it is known that PV systems only generate energy, in general, about 12 hours a day and biogas systems, in theory, can generate up to 24 hours a day, so these comparisons must be put into perspective.

3.1. Avoided emissions

The estimated avoided emissions for generating electricity using biogas and PV systems were 338 and 119 $gCO_{2\ eq}$/kWh, respectively. The discrepancy between the values, in the order of three times, can be attributed to two main factors: (i) the avoided emissions for biogas are higher, as biogas from agricultural residues, by itself, already promotes the significant mitigation of pollutants which would be released freely into the atmosphere in the event of disposal of swine farming waste for open composting or neglect of treatment. So it is important to emphasized, that the production of biogas from agricultural waste, is already the result of mitigating environmental impacts; and (ii) the emissions avoided by replacing the Brazilian electricity matrix are relatively small, as electricity generation in the country is currently around 80% from renewable sources (MME, 2022).

It should be noted that the result of the evaluation of the externality of avoided emissions for biogas was quantified by two factors: avoided emissions, compared to composting and avoided emissions considering the insertion of generation in the current Brazilian electricity matrix. The following values were estimated: 219.73 and 118.50 $gCO_{2\ eq}$/kWh, respectively. The first corresponds to about 65% of the total value obtained and the second 35% in relation to total avoided emissions, due to the use of biogas in the Brazilian electric energy matrix. As for PV systems, avoided emissions of 118.50 $gCO_{2\ eq}$/kWh were obtained, corresponding to 100% of the total value obtained, since it was considered exclusively avoided emissions due to the insertion of generation in the current Brazilian electrical matrix.

The estimated economic value of the externality for the prosumer was around 0.009 and 0.003 US$/kWh, respectively for biogas and PV systems, considering the quotation of C_{Bios} in Brazil. C_{Bios} quotation is significantly lower than similar values practiced in Europe. Considering the current European quotation, the values were 0.030 and 0.010 US$/kWh, respectively for the two sources. For the average value of social carbon costs, S_{CC} , according to Wang et al. (2019) which is 198 US$ per ton of $CO_{2\ eq}$, the values of the externality in question for society were on average 0.067 and 0.024 US$/kWh for the generation of electricity through biogas and PV systems.

The economic value of the avoided emissions externality shows that the generation of electricity using biogas from swine waste has a great advantage over PV systems, demonstrating that, from an environmental perspective, priority should be given to generation using biogas. Considering the electricity consumption rate applicable to rural consumers in Minas Gerais State, in the modality intended for the situation under study, is 0.0709 US$/kWh, this value of the externality obtained from the perspective of society for biogas is equivalent to about 94% of the electrical energy value (CEMIGD, 2023). This reinforces the importance of making thorough assessments of externalities, both in terms of energy balance, but also economics in terms of the value of electrical energy. These results are expressive for society, showing that subsidies for generation through biogas have a greater return than for PV systems and should be prioritized.

3.2. Employment and income

The estimate of the employment and income externality for society resulted in values of around 0.020 and 0.027 US$/kWh, respectively for biogas and PV systems. The highest value was obtained for PV systems, which means that, for society, these systems can be more attractive from the perspective of job and income generation. Despite this, it should be noted that the result refers to the comparison between medium and large system size, that is, greater than 100 kW of installed power.

The result obtained, under the conditions defined in the study, for this externality was about 30% higher for PV systems compared to biogas, but in smaller systems, that is, smaller than 100 kW of installed power, the advantage situation can be opposed (Oconnor et al., 2021). That is, any incentives or allocation of resources specifically aimed at the return on job and income generation must be proposed according to the installed capacity of the plants and type of generating source. This consideration is essential to maximize the intended effects of public policies that encourage this externality.

The highest value obtained was for PV systems, as the L_{COE} value for these systems is less dependent on the size of the generation plant than for biogas. For small-scale biogas generation systems, the externality value tends to be much higher than that obtained in this study, in the order of magnitude of 50 times (Pinto et al, 2023; Silva et al. 2022a). This occurs because small-scale biogas electric power generation systems have low viability and consequently a higher L_{COE} value, which implies higher values for the externality.

Despite the inversely proportional relationship between the externality value and the size of biogas power generation systems, small systems may not be economically viable in most cases. Subsidies to enable small generation systems can be awfully expensive, due to the high L_{COE}. Thus, an alternative is that government incentives be directed to promote cooperation between rural producers, allowing the construction of larger biogas generation systems. A greater depth in the evaluation of this externality tends to allow estimating the ideal size of renewable electricity generation systems, in order to maximize the generation of employment and income and, at the same time, the feasibility of investment in new renewable generation projects, allowing to minimize any economic incentives paid for by society.

3.3. Particular externalities of each generation source

The externality use of biofertilizers was calculated for biogas considering the application of biodigested effluent to replace, completely or partially, the application of commercial fertilizers in crops. Using the avoided cost methodology, it was found that this externality can be worth between 0.05 and 0.16 US$/kWh of electricity generated, depending on the concentration of biofertilizers contained in the effluents. The average value obtained for this externality was higher than the price of electricity by more than 50%, considering the applicable consumption rate (CEMIGD, 2023). That is, there is an externality that may be worth more than the value of the electricity generated.

It should be noted that the evaluation of this externality is considering the avoided costs with fertilizers that would otherwise be purchased. For situations where there is no demand for biofertilizers on the rural property, and the decision is made to sell this material, the results of the externality may be lower. Considering the costs of commercialization of the biofertilizer, the value of the externality can be reduced by about 12% (Silva et al., 2022b). Even with the possibility of reducing the value of the externality, the attractiveness of opting for biogas in relation to PV systems as a form of energy generation becomes evident.

The estimate of economic value for the externality use as a building material was made considering that photovoltaic panels can be used as a building element. This possibility is due to the fact that PV modules are waterproof and can be installed directly as a roofing element. The economic value for this externality, considering the perspective of the rural prosumer, ranged from around 0.0004 to 0.0010 US$/kWh. The range of values was obtained considering avoided costs with tiles and lighter roof structures.

It should be noted that even considering the extremes of the ranges, the externality value obtained for biogas was significantly higher than that obtained for PV systems, on average about 150 times greater. The major difference is due to the avoided costs with constructive systems, made possible by the PV systems, which is made possible only in the installation of the generation systems, since the biofertilizers for the biogas are produced continuously. This large difference, represented quantitatively in the comparison of externalities, denotes the importance of evaluating the externalities of each renewable generating source. Moreover, due to the high economic value, the evaluation of externalities can be a decisive criterion in the definition of generation energy source to be implemented from the perspective of the rural prosumer.

3.4. Qualitative assessment of externalities

3.4.1. Power quality

The externality, power quality, was discussed mainly from the perspective of the electric power utility. This externality can be strongly dependent on the generation energy source adopted, either through biogas or PV systems. In general, power quality is related to: reducing losses, improving both the voltage profile and the reliability of the electrical power system. The increase in power quality can be achieved by the insertion of distributed generation from either biogas or PV systems (Kamarudin, Hashim and Musa, 2019).

The allocation of distributed generation systems, according to priority locations or regions defined by the electricity utility, may allow the maximization of benefits. Increased power quality can, according to Duong et al. (2019) imply reduction of losses, improvement of voltage profile and harmonic distortions. Along these lines, a thorough assessment by electric utility may even allow incentives to be provided for the strategic implementation of distributed generation sources.

3.4.2. Postponement of investment in transmission and distribution

The externality, postponement of investment in transmission and distribution of electrical energy, can be achieved with the insertion of distributed generation through biogas or PV systems, due to the decrease in current flow in the network. The externality essentially depends on the type and size of installed distributed generation, possibility of energy storage and also on the load growth rate. Distributed generation systems, when allocated at strategic points, can allow the postponement of investment in system reinforcement works installations (Minnaar, 2016).

Although distributed generation allows, in certain situations, a significant postponement of network reinforcement or even the avoidance of reinforcement, this externality is still not widely recognized. This externality must be internalized as an opportunity for electric utility, mainly so that forms of incentive can be proposed for strategic locations (Cossent, Gómez and Frías, 2009). It should be noted that this externality may also be associated with energy storage, as storage can allow the postponement of reinforcement works by enabling changes in the load curve.

3.4.3. Energy storage

The externality energy storage is a strategic resource when considering the generation of energy through biogas and can be an advantage in relation to PV systems. The externality can provide postponement of network expansion, improvement in the voltage profile and strategic reserve. It should also be noted that conventional storage in PV systems by the use of batteries generates high costs for the electric utility, that is, an alternative such as biogas seems highly relevant for electric utility (Mehrjerdi, 2019)

PV systems can also rely on energy storage through a bank of batteries; however, they are additional and costly systems, which is why they were not considered in this study. Furthermore, it should be noted that the intermittency of PV systems can generate additional costs to the electrical system with energy storage and/or the construction of other storage plants to enable greater insertion of PV systems (Li et al., 2021). The greater consistency of electricity generation through biogas can be a great strategic advantage for electric utility, especially if the injection control of these units is allowed to the prosumers by the regulator agency.

The storage of biogas inside biodigesters can benefit not only electric utilities, but also the prosumers themselves. The externality in question may be relevant to the prosumer who opts for biogas, as the cost of losses non-supplied can reach about 75 times the value of electricity (Gorman, 2022). The energy storage externality, considered for biogas, has advantages over other backup energy supply sources such as lower pollutant emissions and significantly lower generation costs for the rural prosumer (Sanni et al., 2021). This externality may be even more relevant for prosumers who have more sensitive loads and/or depend on electricity to store perishable products.

3.4.4. Modularity of PV systems

The modularity externality of PV systems is a strategic and exclusive advantage of these systems in relation to generation through biogas. PV systems are modular, that is, they allow the installation of practically the required power or a fraction of it, if necessary. These systems are composed of independent generation modules and can be rearranged to compose projects of different scales (Kumar et al. 2019). Modularity has evolved along with the converters technology, with benefits such as improved power quality and project scalability (Elsanabary et al., 2020).

Modularity allows PV systems to tend to be viable for a wider range of installed power. Biogas systems are dimensioned according to the initial project and are limited according to the commercial capacity of the required equipment. Another relevant point is that PV systems can be expanded according to demand, whereas for biogas systems the eventual expansion is more limited and may involve the need for major changes in existing installations.

That is, the economic viability of energy generation systems using biogas may strongly depend on the scale of the project. In general, for small swine farms, it may be feasible to generate electricity using PV systems, whereas for biogas it is usually feasible for larger installations (Oliveira et al., 2022).

3.4.5. Cogeneration

The cogeneration externality is an exclusive externality of biogas. For PV systems, there is no possibility of using heat, except if thermo-photovoltaic solar systems were used (Lamnatou and Chemisana, 2017). The use of heat for PV systems depends on the adoption of specific equipment in the design phase, which generates significant additional costs for the installation. Therefore, the use of heat in PV systems was not considered in this research.

It should be noted that the use of thermal energy from biogas cogeneration can be used multiple times and/or for specific situations. The heat can be used in swine farming processes, either for heating the facilities (Wu, Cheng and Chang, 2020). Another possibility is to use heat to optimize the generation of electrical energy. The latter may allow greater biogas production by heating the biodigester or maximize the efficiency of electrical generation by harnessing thermal energy (Freitas et al., 2022).

3.4.6. Quality of life improvement

For society, the externality quality of life is positive for both sources of electricity generation, biogas and PV. For electricity generation systems using biogas from the treatment of organic waste, this externality is expected to be greater than for PV systems. This is because generation using biogas is an environmental treatment, that is, it reduces pollutant emissions, but also the pollution of water sources. Whereas PV systems only do not emit pollutants during the power generation.

The externality quality of life improvement is extremely comprehensive and difficult to quantify economically, as improved quality of life is related to environmental quality and several other factors. Actions to mitigate pollution and environmental degradation are essential to shape people's quality of life, thus, the influences of environmental preservation are directly related to the improvement of well-being (Wu et al., 2020). Pollutant emissions can cause serious impacts on the health of the population, especially for the most vulnerable groups. The greatest impacts may still be associated with regions with greater social inequality (Hill et al., 2019).

The health impacts are extensive, including psychological health. (Sivarethinamohan et al., 2021). Thus, improved techniques to assess human susceptibility to air pollutants must be implemented. It is known that pollutant emissions directly affect the level of happiness of the population, this was evaluated in studies that consider data from social media (Zheng et al., 2019). When exposed to high levels of air pollution, the general population is at greater risk of mortality, worsening emotional state and reduced productivity of workers who perform their activities outdoors and indoors (Kahn and Li, 2020).

The cost-effectiveness of pollution control has already been evaluated and is economically viable by several metrics, for example: the cost of a plan to control pollution in regions of China has shown that the amount invested is lower than the economic impact of premature deaths and the reduction in public health expenditures. This indicates that the cost-effectiveness of these plans is attractive, with the benefits being able to exceed the cost by more than five times (Zhang et al. 2019). Directing health resources towards air pollution control can be an alternative (Thair et al., 2021). Factors such as pollution can influence the emigration of people. Migratory and environmental policies must be related and considered (Germani et al., 2021).

Still on the quality of life, in general, the generation of PV electricity does not cause direct impacts on water resources, however, the generation of electricity through biogas can improve sanitation. The biodigestion process significantly improves water quality by reducing the organic load. This may allow mitigating the pollution of the water environment and consequently enable sports and leisure activities. Improved water quality, therefore, is directly related to quality of life (Hsu, Lin and Jhang, 2020).

4. Evaluation of public policies

Public policies must be aimed at improving people's quality of life, whether, for example, to mitigate the harmful effects of environmental pollution or promote the restoration of the green landscape. In this research, the value of estimated externalities reinforces their importance in proposing public policies to encourage renewable sources. What is expected is that the consideration of externalities can contribute to a better understanding and by doing so a tool to promote a more sustainable development.

4.1. World context

Public policies for the promotion and regulation of biogas are not yet consolidated worldwide, even though biogas from agricultural waste has shown significant environmental benefits. Recognizing the advantages of biogas through a more holistic view of opportunities can be the solution for assertive planning, providing more security for investments and incentives in this renewable source (Gustafsson and Anderberg, 2021). Distrust on the part of investors, the proximity of biogas production plants to residential areas and the lack of subsidies are the biggest obstacles observed for the promotion and implementation of new biogas production projects in France (Bourdin, Raulin and Josset et al., 2020).

In Sweden, a government incentive program strongly aimed at promoting renewable energies subsidizes up to 30% investment in biogas production plants. Feed-in tariffs also massively encourage renewable energy projects in Spain and Germany. In Denmark, subsidies for renewable energy generation are also significant since the 1970s (Ferreira et al., 2012). What is concluded is that countries that invest in economically attractive feed-in tariffs, simplified and agile regulation allow a significant use of the biogas production potential, and speed up the planning implementation.

The attractiveness of power generation plants using biogas has grown worldwide, however, only large plants tend to be more economically attractive. Therefore, public policies, mainly with subsidies, are fundamental for the viability of small and medium-sized projects (Piñas et al., 2019). Public policies can be a solution to promote the development of biogas production, that is, considering regional specificities (Bourdin, Raulin and Josset et al., 2020). A balance between different types of policy instruments and regulatory mechanisms must be strengthened to constantly support biogas production (Chung et al., 2022).

4.2. Public policies in the Brazilian context

Due to the discrepancy in economic value between the externalities observed for biogas and PV systems, there is a need to review Brazilian policy, as it promotes the same incentives for different renewable sources. The disparity in values between externalities from society's perspective denotes those equal incentives for renewable sources are not adequate, as incentives must be proportional to the economic return for society. A single policy can promote disparity in the development of renewables, perhaps prioritizing the less advantageous ones. The attractiveness of investments in PV systems in Brazil is superior to biogas in many situations, which can be proven by the uneven growth between these two sources of electricity generation in the country (MME, 2022). A more detailed consideration of the externalities of different renewable energy sources may be one of the ways to reduce these disparities.

What is expected is that the current policy of net metering tariffs, i.e. compensation system, Brazilian can be revised providing opportunities for the development of renewables according to the benefits they present. It is expected from the Brazilian government credit policies, subsidized technical assistance, structuring of an institutional and legal environment that reduces uncertainties and enables sustainability and profitability for all agents and renewable sources. That is, the comparative evaluation of externalities can allow the allocation of resources and the elaboration of public policies that allow the development of the renewable energy matrix, maximizing those renewable sources that are most beneficial to society. Government policies are therefore considered vital to overcome obstacles to the development of biogas production (Chung et al., 2022).

It is then considered, at first, that subsidies greater than 30% of the initial investment are necessary to make biogas projects viable in Brazil. The purchase of energy by the Brazilian government at a higher price could enable projects to generate electricity in Brazil using biogas (Piñas et al., 2019). It is evident that energy planning policies specific to each source of electricity generation can rely on exclusive feed-in tariffs. In principle, the size of the subsidy should follow the social cost of carbon (Kaiser et al., 2020).

4.3. Externalities evaluation as a strategic factor

A strategic factor for planning may be government incentives to internalize externalities from the perspective of prosumers. That is, for the prosumer who has the possibility to choose a particular source of generation, having knowledge of externalities can be a decisive factor in the design phase. Brazilian rural producers, due to lack of qualified support and negative experiences in the past, may be unaware of the economic effect of externalities and therefore choose less attractive alternative sources of generation.

The importance of government investment to enable the training of qualified professionals and to make technical materials available can be precious alternatives to promote the development of renewable energy sources. The dissemination of knowledge and information can allow the selection of more adequate sources and with greater economic viability for prosumers. In other words, technical support, especially for biogas, can help maximize the development of new generation plants. It should be noted that many incentive programs for renewables, without foundation and technical support, have already failed (WANG et al., 2016).

The strategic advantages of the externalities of distributed energy generation can also be an opportunity for Brazilian electric utilities, even so the incentive for implementation by the electric utility is not yet a reality in Brazil. Rigid regulation, combined with the participation of a relatively small number of large companies in the sector, can be an obstacle to the implementation of incentives. This suggests the need for new regulation for the electricity sector.

Despite so many benefits, Sovacool, King and Yang (2021) state that the study and determination of externalities is an area that is still not very well defined, and in general dependent on points of view, as well as contextualization in time and space. They report that several studies deal with externalities but do so superficially or only qualitatively. That is, what is expected is that public policies enable greater access to mechanisms for internalizing and taking advantage of externalities, providing more economic benefits by improving both deeper knowledge and the vision of different points of view, such as those of prosumers, the electric utility and society. Thus allowing a more real economic evaluation of projects.

5. Conclusions and policy implications

A series of externalities of the distributed generation of electric energy, through the production and burning of biogas from organic residues of swine farming and by solar PV systems were analyzed in this research. The externality with the highest economic value from the perspective of the prosumer was biofertilizers production for biogas and avoided emissions for PV systems. For society, the externality with the greatest economic value was avoided emissions for biogas and employment and income for PV systems. For the set of externalities studied, those of biogas have greater economic value than those of PV systems, both for society and for the consumer. On average, the quantitatively assessed externalities of biogas can be worth about 11.8 times more than those of PV systems to prosumers or 1.7 times to society.

It was qualitatively demonstrated that electric utilities have many opportunities with distributed generation and that regulatory agencies, together with society as a whole, need to review the current assessment model both energetically and economically. The externalities, qualitatively evaluated from the perspective of the rural prosumer, were initially discussed in this research. It is worth noting the importance of assessing externalities as a first step towards internalizing them in economic analyzes and consequently improving the economic evaluation.

The discrepancy of values between externalities evaluated quantitatively and the importance of externalities evaluated qualitatively reinforce the need to promote the production of biogas in Brazil. Government-regulated incentive programs must be reviewed individually for each source of renewable generation. Standing out, the high economic value and the particularities of externalities that reinforce the importance of considering them in energy planning. The regulatory agencies need to continuously intervene as a way to make the rigid and old deregulation of the system aware of other factors such as the externalities listed, aiming to further expand the insertion of distributed generation. The inclusion of the possibility of negotiation between the electric utility and prosumers towards the allocation of distributed generation, may allow prioritizing investments in more advantageous renewable energy sources.

It is indicated that in future studies that a greater number of externalities be evaluated quantitatively, deepening the results achieved. Furthermore, other sources of renewable energy generation must have their externalities evaluated to enable collaborating with energy planning that includes more than one renewable energy source, as it is the case in most countries. Occasional or regional studies can be carried out based on the proposed methodology and can allow for a deeper economic assessment for the implementation of the energy planning.

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