Renewable and Sustainable Energy Reviews 101 (2019) 146–157

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The Brazilian market of distributed biogas generation: Overview, technological development and case study

F.F. Freitas[a], S.S. De Souza[b,*], L.R.A. Ferreira[c], R.B. Otto[c], F.J. Alessio[d], S.N.M. De Souza[e], O.J. Venturini[a], O.H. Ando Junior[b]

[a] Excellence Group in Thermoelectric and Distributed Generation - NEST / IEM, UNIFEI, Federal University of Itajubá, Av. BPS 1303, CP 50, Itajubá, MG CEP 37.500-903, Brazil

[b] Department of Renewable Energies. UNILA, Federal University of Latin American Integration, Av. Sílvio Américo Sasdelli, 1842 Foz do Iguaçu, PR, Brazil

[c] Automation and Simulation of Electrical Systems Laboratory (Lasse), PTI, Itaipu Technological Park, Av. Tancredo Neves, 6731 Foz do Iguaçu, Paraná, Brazil

[d] Food and Agriculture Organization of the United Nations (FAO). Project Coordination Unit for Southern Brazil. UDC, University Center, Foz do Iguaçu, PR, Brazil

[e] Postgraduate Program in Energy Engineering in Agriculture – PPGEA. UNIOESTE, State University of Western Paraná, Cascavel, PR, Brazil

ARTICLE INFO

Keywords:
Biogas technologies
Brazilian energy matrix
Biogas plants
Distributed generation
Colombari farm

ABSTRACT

Biomass is a potential energy source for the diversification of the Brazilian energy matrix. In this context, the biogas produced from the anaerobic digestion of residues is a relevant renewable resource that plays a significant role in the mitigation of environmental problems and the local generation of electric energy. This review presents the scenario of the biogas production and electricity distributed generation within the Brazilian context. Firstly, it presents an overview of the electric energy generation from biogas and the Brazilian plants that compose this electric matrix. Secondly, the main technologies to produce biogas and the possibilities of its use, followed by the comparison of technologies for distributed generation of electric energy from biogas in the Brazilian market. To illustrate the application of biogas technology, this paper presents a case study of a biogas plant operation and its connectivity to the grid, the Colombari Farm. The information presented here aims to enhance and to foment the recovering of biomass residues to produce biogas via anaerobic digestion and its utilization to generate electricity. Although the case study considers a specific plant in Brazil, the information and results presented can be applied to others areas of the country or regions of the world, so contributing to promote the expansion of biogas plants to generate electricity. Finally, a future perspectives section describes the practical implications of the biogas production and electricity generation in rural and urban areas and its contribution to the implementation of Brazilian environmental and social policies. This review also is useful to support the research development of biogas for electricity production.

1. Introduction

Renewable energy is, by definition, sustainable and clean. Its usage offers the opportunity to restrain the increasing depletion of the fossil resources as well as the environmental impacts resulting from the indiscriminate use of non-renewable resources. Over the last two decades, the representation of renewable energy in the global power generation matrix has experienced a significant growth. In 2014, 59% of the global net addition of power generation capacity came through renewable energy [1,2]. China is the world leader in renewable energy generation being responsible for 21% of the world's renewable energy share, while the United States provides about 11% of the global share [3,4]. Brazil figures in the third position with 10%, but aiming to increase its share to around 19% by 2020 [5,6].

Even though the shared use of the alternative energies is still much lower when compared with the consolidated ones, the growth of renewable sources in the world energy matrix is increasing over time, as can be seen in Fig. 1 [4,7,8]. Based on the scenario, one can see the importance of giving by the world's largest economies to the diversification of their energy matrix, as well as the viability of using renewable energy sources.

Recent politics at a national level demonstrate that Brazil is following the global tendency towards clean energy and is committed to the strategy of maintaining its historically renewable matrix, now

* Corresponding author.
E-mail addresses: flaviofereirafreitas@gmail.com (F.F. Freitas), saengquimica@gmail.com (S.S. De Souza), liz.ferreira@pti.org.br (L.R.A. Ferreira), rodrigobueno@pti.org.br (R.B. Otto), felipe.alessio@fao.org (F.J. Alessio), ssouza@unioeste.br (S.N.M. De Souza), osvaldo@unifei.edu.br (O.J. Venturini), oswaldo.junior@unila.edu.br (O.H. Ando Junior).

https://doi.org/10.1016/j.rser.2018.11.007
Received 15 June 2018; Received in revised form 16 October 2018; Accepted 4 November 2018
Available online 17 November 2018
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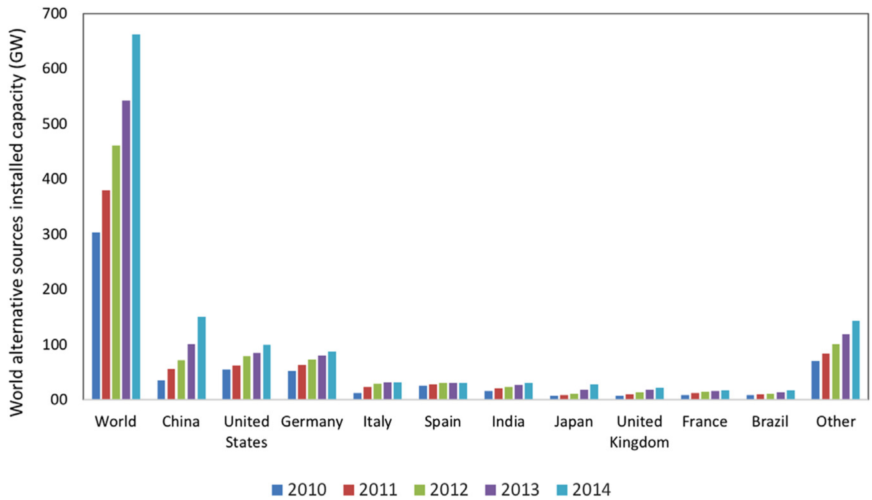

Fig. 1. World alternative sources installed capacity - top ten countries in 2014 (GW) [4].

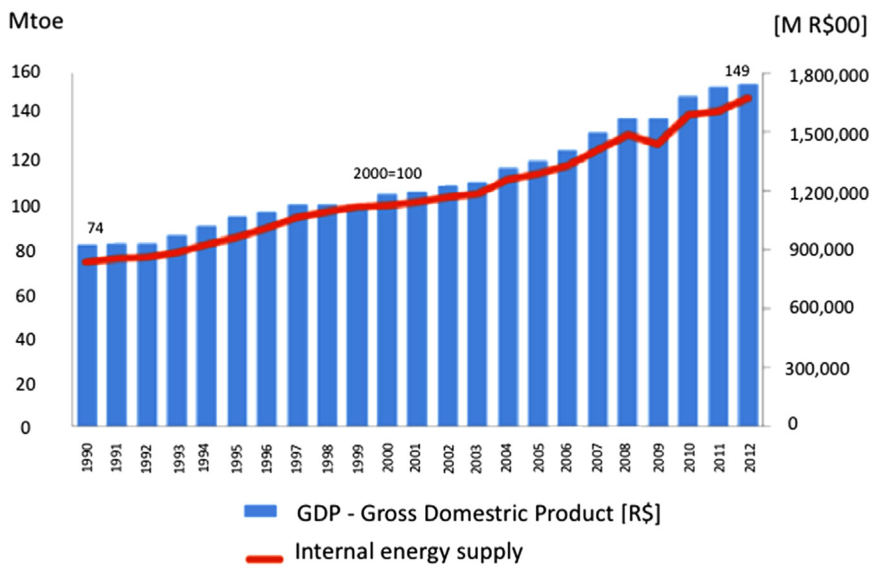

Fig. 2. Demonstration of Gross Domestic Product growth and Internal Energy Supply (1990 to 2012) Adapted from [9].

combined with its policy of energy safety. The Brazilian concern can be explained by its economic growth in the last two decades, which consequently has led to an increase in the country's primary energy consumption by more than one-third, as observed in Fig. 2. [9].

In 2012, Brazil was the eighth largest electricity generator in the world with a total generation of about 538 billion kWh of electricity, which corresponds to approximately 2% of world electricity production during that period [10]. According to the Energy Information Administration - EIA [10], about 451 billion kWh of electricity generated in 2012 came from renewable sources, and 91% of this amount (411 billion kWh) was generated from hydropower, making Brazil the third largest renewable energy generator and the second largest global hydroelectric generator in 2012 [10]. According to data, Brazil is the world's second largest producer of ethanol (26.2 million cubic meters in 2010 from sugarcane) and the world's largest exporter of ethanol, producing 76,154 m^3/day of ethanol in 2013, an increase of 18% in relation to the previous year [11–13]. Although Brazil has experienced the increase of its energy production by ethanol and hydropower, the renewable energy share in the Brazilian energy matrix decreased from 49% in 1990 to 42% in 2012 (Fig. 3), especially due to the substitution of firewood (counted as 100% renewable) and climate conditions.

The production of energy from renewable sources greatly depends on climatic conditions. In the current scenario, the vulnerability of the Brazilian energy matrix considering its reliance on hydroelectric energy and consequently its dependence on the rainfall regime can compromise the country energy security. Brazil has already experienced major problems of electricity supply as the result of a great period of drought in 2001, which compromised the capacity of the reservoirs, drastically reducing hydro generation capacity [6,14,15]. Driven by the 2001 energy crisis and the constant climate changes, different initiatives have been developed in Brazil to increase the internal offer of renewable energy, in association with the pursuit of a low carbon economy [16,17]. In mid-2004 the Brazilian government implemented the Program of Incentives for Alternative Electricity Sources (PROINFA in Portuguese), one of the world's largest mechanisms in the feed-in tariff (FIT).

Besides establishing legal mechanisms to stimulate the electricity generation from three different energy sources (wind, biomass and small-scale hydro) [18–21], the PROINFA has signalized the investors about the seriousness of the renewable energy politics in Brazil. For the year 2018, the program has a budget of R$ 3.4 billion [22]. The number clarifies the present tendency in the electric sector to invest in the diversification of the Brazilian energy matrix, the maintenance of its renewable predominance, and the Brazilian prominent and pioneering

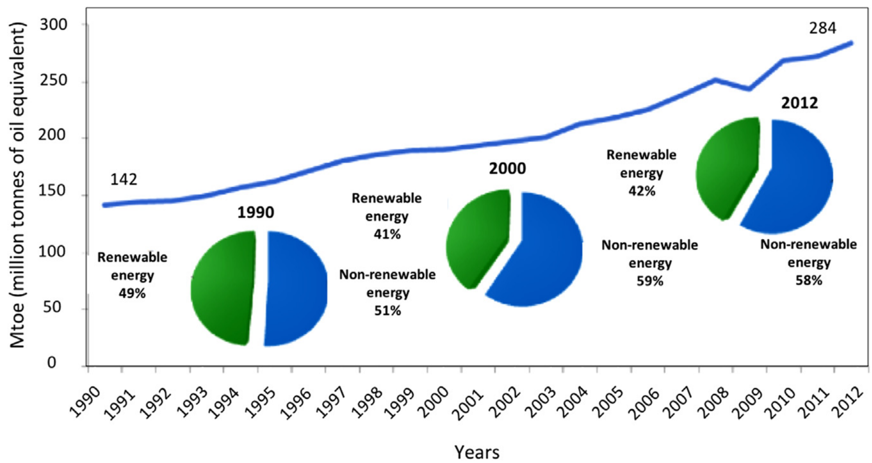

Fig. 3. Brazilian Energy Matrix. Adapted from [12].

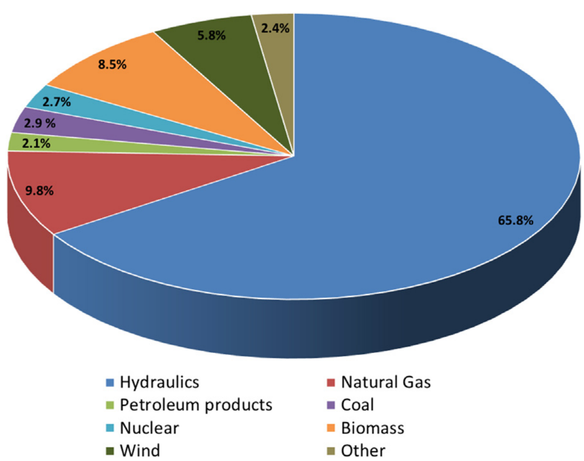

Fig. 4. Brazil electricity generation by source, according to the total capacity of electrical generation in GW. Based on [4].

role in the global trend of utilization of new renewable sources [23,24]. Biogas still represents a small part of the biomass plants, which is responsible for 8.5% of the total electrical energy generated in Brazil, according to the National Energy Balance (2017) (Fig. 4). Brazil remains highly dependent on two sources: hydro and natural gas [4].

Among the alternative sources used in Brazil stands out the solar, wind and biomass [7]. Although they all play a significant role in the renewable energy matrix, the interest of this paper is about the biomass sector, especially the biogas production. As argued in previous works, the biogas has the potential to contribute significantly to generate electricity in Brazil [25,26]. Other know positive effects are the decentralization of the territorial distribution of energy, prevention of environmental pollution, the reduction of fossil fuels consumption and the creation of sources of income and jobs within the vast rural area of Brazil [27], which has a territorial extension with 8.5 million km^2.

This review intends to carry out a general survey on the biogas production technology for electricity generation, inserted in the context of distributed generation for the Brazilian market, considering the significant economic effects for the large, medium and small entrepreneur due to the use of this technology. In addition, the review presents the case study of the first biogas minigeneration plant connected to the grid, installed and in operation in Brazil. The information and results presented can be applied to others areas of the country or even in the world, so contributing to encourage the use of this important resource (the biogas) to generate electricity.

2. Overview of the electric energy generation from biogas in Brazil

Biogas production technology is still incipient in the country, and over a long period of 40 years (1970–2010), it did not receive the appropriate importance, being considered a by-product with no economic value. From 2010, biogas began to be used in energy generation, being considered an energy asset and no longer an environmental liability [26,28].

The composition of biogas produced from the anaerobic digestion is directly related to the type of decomposed organic matter. Thus, considering the amplitude of existing biomass, the Brazilian Electricity Regulatory Agency (ANEEL in Portuguese) classifies the biogas used to produce electricity into four large groups: forest residues, urban solid waste (UW), animal waste (AW) and agro-industrial waste (AIW). In this classification, the use of wastes predominates in the production of biogas aiming the generation of electricity.

Waste-to-energy technologies consist of any waste treatment process that produces energy in the form of electricity, heat or fuels from a waste source. These technologies can be applied to several types of waste: from the semi-solid to liquid and gaseous waste [29,30].

The global impacts of solid waste are growing fast. Solid waste is a large source of methane, a powerful Greenhouse Gas (GHG) that is particularly impactful in the short-term. Solid urban waste, which represents the predominant source for biogas production, contains portions of substances that have a high potential for biogas production, such as organic matter (food waste) [31,32]. On the other hand, animal waste is basically produced by animals and there is a wide range of animal wastes that can be used as sources of biomass energy. The most attractive method of converting these organic waste materials into useful fuel is through anaerobic digestion, which produces biogas that can be used to power internal combustion engines or small gas turbines, burnt directly for cooking, or for space and water heating [33].

Agro-industrial wastes are rich in bioactive compounds, especially those originated from the productive material process of fiber, leather, wood, and food. These residues, first seen by companies as a negative output, now have the potential to generate different products, such as the biogas. Table 1 shows the Brazilian plants that compose the electric matrix and which uses biogas from urban, animal and agro-industrial solid waste as an energy source.

As noted above, more than 95% of all electricity produced from biogas comes from urban solid waste facilities [34]. All these power plants are distributed in Brazil, although they are mainly concentrated in the South and Southeast of Brazil as shown in Fig. 5.

Each marker of Fig. 5 represents a unit and by clicking the marker at the platform, it shows the unit category, the substrate source, the

Table 1
Power plants from biogas [34].

Power Plant	City - State	Source	Supervised Power (kW)	Participation by source (%)
Salvador	Salvador - BA	Biogas - UW	19,730	96.77
São João Biogás	São Paulo - SP	Biogas - UW	21,560	
Energ-Biog	Barueri - SP	Biogas - UW	30	
Asja BH	Belo Horizonte - MG	Biogas - UW	4278	
Arrudas	Belo Horizonte - MG	Biogas - UW	2400	
Ambient	Ribeirão Preto - SP	Biogas - UW	1500	
Biotérmica Recreio	Minas do Leão - RS	Biogas - UW	8556	
Uberlândia	Uberlândia - MG	Biogas - UW	2852	
Asja Sabará	Sabará - MG	Biogas - UW	2852	
CTR Juiz de Fora	Juiz de Fora - MG	Biogas - UW	4278	
Itajaí Biogás	Itajaí- SC	Biogas - UW	1065	
Termoverde Caieiras	Caieiras - SP	Biogas - UW	29,547	
Guatapará	Guatapará - SP	Biogas - UW	5704	
Bandeirantes	São Paulo - SP	Biogas - UW	4624	
Curitiba Energia	Fazenda Rio Grande - PR	Biogas - UW	4278	
Tecipar	Santana de Parnaíba - SP	Biogas - UW	4278	
Ronaldo de Freitas Silva	Uberlândia - MG	Biogas - AW	120	1.73
Fazenda Nossa Senhora de Fátima	Perdizes - MG	Biogas - AW	175.2	
Unidade Industrial de Aves	Matelândia - PR	Biogas - AW	160	
Unidade Industrial de Vegetais	Itaipulândia - PR	Biogas - AW	40	
ETE Ouro Verde	Foz do Iguaçu - PR	Biogas - AW	20	
Star Milk	Céu Azul - PR	Biogas - AW	110	
Fazenda da Luz	Abelardo Luz - SC	Biogas - AW	810	
Granja Makena	Patrocínio - MG	Biogas - AW	80	
Ajuricaba	Marechal Cândido Rondon - PR	Biogas - AW	80	
Fazenda Nossa Senhora do Carmo	Ituiutaba - MG	Biogas - AW	80	
Granja São Roque	Videira - SC	Biogas - AW	424	
Cogeraçao Bio Springer	Valinhos - SP	Biogas - AIW	848	1.5
Adelar Piaia	Três Passos - RS	Biogas - AIW	100	
Cetrel Bioenergia JB	Cachoeirinha - PE	Biogas - AIW	874	
Total			**121,453.2**	**100**

average biogas production, the situation of the plant (if in phases of installation or operation), the size, and the energy application of biogas (thermal, electrical, mechanical or Biomethane/Vehicle Natural Gas) [35]. The substrate source is thus classified as shown in Fig. 6. The energy potential of these residues in Brazil and the State of Parana have already been studied [25].

The Biogas Map is a public and online platform created by the International Center of Renewable Energy (CIBiogás) in partnership with the International Center of Hydroinformatics (ICH) and with the support of Brazil-Germany Project to promote the use of Biogas in Brazil (Probiogás). The initiative shows the feasibility of the biogas power plants in Brazil and helps to develop the biogas Brazilian sector through the dissemination of information about the production potential, existing production units, available technologies, research and development projects, financing lines, legislation and regulations, consultants and suppliers [35].

The potential for biomass in the Brazilian market for the production of biogas and its use for electricity generation has been reported by Ferreira et al. [25]. In 2015, there were 127 biogas plants in Brazil using agricultural and industry residues, bio-waste, sewage sludge, and landfill gas, which produced about 1.6 million Nm^3/day (584 billion m^3 biogas/year), representing an electricity generation of 3835 GWh [36,37]. The installed biogas electricity generation capacity has increased significantly, reaching 196 MW in 2015 and 450 MW in 2016 [38].

The increases in biogas production in Brazil is a result of its economic and technical viability. The production of biogas occurs from different organic materials, such as animal waste, urban and industrial solid waste. About the urban waste subject, a study conducted by [39] highlighted the potential of electric energy generation of biogas from landfills in Brazil and presents the economic viability of these biogas plants. The author argues that for biogas energy plants to be viable from urban waste, the population could not be less than 200,000 inhabitants. In smaller municipalities, the viability of the projects relies on public policies. Regarding the industrial segment, the work presented by [40] clarifies the economic and technical viability of biogas production from vinasse, a residue of the sugar cane industry. In their work, an area equivalent to 6000 ha (considering sugarcane processing in autonomous plants) or 14,580 ha (considering the processing of sugarcane in joint plants) is required to achieve economic viability. Other studies also highlight the economic viability from anaerobic digestion to the production of biogas [41,42]. On the subject of animal waste, a recently study by Rockenbach et al. (2016) demonstrated that the generation and use of biogas for the production of electric energy on a large scale is feasible with a daily operation of the generators per at least 10 h and a return of the investment predicted from 70 to 80 months [43]. A study carried out by Pasqual and coworkers (2018) exemplifies the viability of small-scale biogas production and generation of energy based on the energetic condominium of milk producers [44]. In both cases, it is necessary to take into account the several factors that influence the viability of biogas from animal waste. The equipment used, the investment needed to install the plant, the plant's production potential, the electric energy price for the rural area, the chemical composition of the waste, along with other local factors, plays an important role to determine the economic and technical viability of the plants [43,45,46].

The positive environmental impacts of biogas production from organic waste also motivates the sector in Brazil, whether as a solution to an environmental issue or the supply change of energy. Studies that aim to show the environmental gains of the process generally carry out the application of the Life Cycle Analysis (LCA). LCA is a standardization methodology that evaluates the environmental performance of a product or process throughout its life cycle and is divided into four stages: goal and scope definition; life cycle inventory, impact assessment and interpretation (ISO 14040/2006) [47]. Other researchers conducted many studies applying LCA to biogas systems in order to assess the environmental impacts associated with the use and production of biogas as an energy source [48,49]. In the Brazilian context, the use of

Fig. 5. Brazilian Map of Generation Centers of Biogas Production. The markers, blue, yellow and green indicates the unit size, classified as large (more than 12,000 m^3/day), medium (around 2,000 to 12,000 m^3/day) and small size (less than 2,000 m^3/day), respectively. [35].

biogas plants for the generation of energy from landfills or the incineration of methane has shown excellent results when compared to traditional waste treatment systems [50]. Among the possibilities and combinations of treatments, the generation of electric energy from the biological mechanical process plus the use of incineration obtained the best environmental results [51]. Although there are still some political, social and economic issues to the implementation of energy generation plants from solid waste, environmental gains are expressive and can contribute significantly to the reduction of CO_2 emissions at the atmosphere.

2.1. Production and generation of electricity from biogas

Studies have shown that biogas can be produced from various raw materials by thermochemical or biochemical conversion [52]. Direct combustion of the biogas and its use in internal combustion engines are the main types of biogas application. Fig. 7 shows the flow chart summarizing the possibilities of using biogas as an alternative fuel [53,54].

In the process of direct combustion, the biogas is burned in combustion chambers of boilers, heaters, dryers, and the heat released is used in production processes. On the other hand, the biogas can be burned in prime movers (internal combustion engines or gas turbines) to produce electricity or mechanical power. The internal combustion engines convert the biogas energy into mechanical energy, which is used directly to power a load (a pump, a fan, etc.) or a vehicle, or they can be connected to the motogenerator, which can be used by rural and agro-industrial properties for the distributed generation of electricity [55]. Therefore, the main prime movers used for electricity production are internal combustion engines and gas turbines.

2.2. Technologies for biogas production

The process of distributed generation from waste biomass involves the transformation of waste into biogas with the use of biodigesters. The amount of biogas produced varies depending on many different factors such as raw materials, pre-treatment technology, temperature and time in the reactor. The organic matter degradation that occurs in natural situations can also be reproduced in biodigesters [56,57].

Basically, the degradation procedures are divided into aerobic (in the oxygen presence) and anaerobic digestion (in the absence of oxygen). Anaerobic digestion has become an established and proven

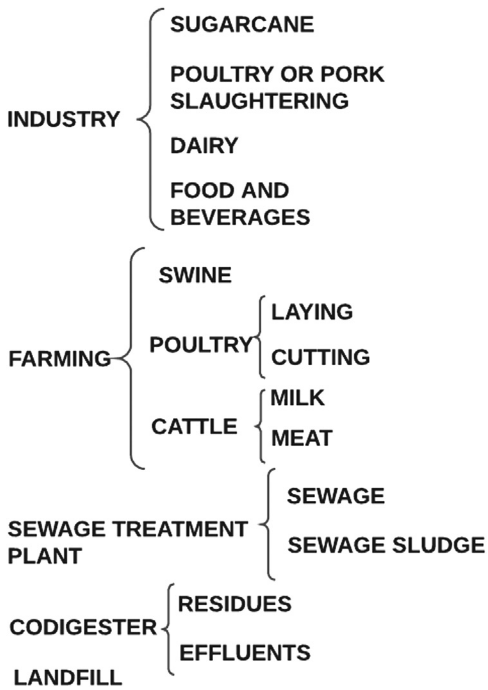

Fig. 6. Classification of the substrate source for each sector [35]

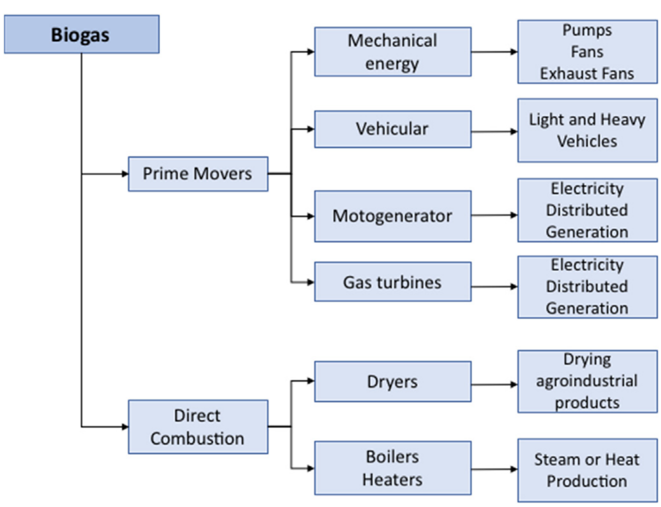

Fig. 7. Flow chart summarizing the possibilities of biogas use [53,54].

technology as a means of managing solid as well as liquid organic wastes [58,59]. It requires a certain hydraulic retention time, which depends on the operating temperature of the biogas plant, the initial temperature, and agitation conditions. There is a range of variables that increase the complexity of the biogas production and it prevents a direct relationship between the quality of the gas and the technology used to produce it. In the total oxygen absence, mixed microorganisms colonies act and find ideal conditions to proliferate, feeding on soluble solids in the biomass under treatment, which causes the organic matter degradation [28,60]. The employment of anaerobic digestion technology for waste treatment is possible and desirable given that it contributes to environmental preservation, makes modern production systems viable, and optimizes the enterprise's cost/benefit ratio [26].

In Brazil, a country with a tropical climate with large territorial extensions and a great biodiversity, it is possible to perform anaerobic digestion in biodigesters with low aggregate technology. In the Brazilian model, predominate the biodigesters directly connected to the production systems of stacked animals and close to the lands that will

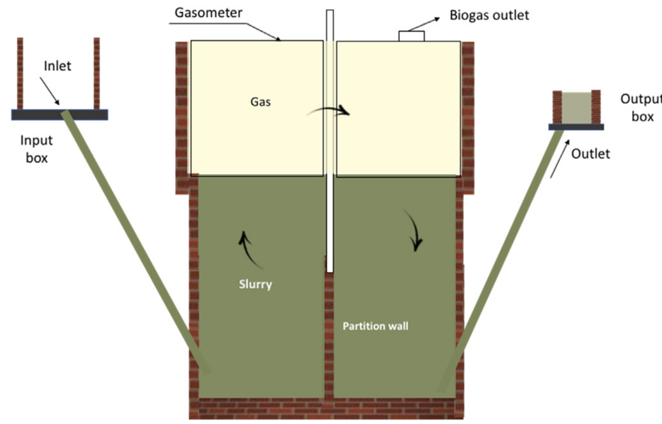

Fig. 8. Indian model biodigester. Based on [67].

receive the digestate. The biogas generated in the individual biodigesters are channeled into pipelines that transport it to the centers of use and applications [28]. It is worth noting that biodigester technology is already available, however, the greatest barriers do not seem to be technological but political and regulatory in nature [26].

2.2.1. *Biodigesters types*

China and India dominate the best technologies biodigesters construction. The main objective of China is to obtain biofertilizers for food production, whereas, India seeks to reduce the energy deficit [61,62].

2.2.1.1. Indian model biodigester. In this model, the fermentation stage is faster. The biodigester consists of the main tank (fermentation chamber) where the biomass digestion will occur. The main tank is usually buried in the ground, thus taking advantage of the low soil temperature variability to favor the action of bacteria. The main tank is divided into two chambers by a partition wall that forces the circulation of the material throughout the biodigester (see Fig. 8). The biogas generated is retained in a metal bell-shaped cover (the campanula) installed above the biodigester, that regulates the internal pressure [63]. Due to the functionality of this model, in the 90's it was the most used in Brazil [64–66].

The main advantage of this model is the stability of the exhaust pressure of the biogas, due to the floating campanula, which in turn presents a high cost, a disadvantage for the project. Therefore, a comparative and economic analysis should be performed to determine the best technology for the specific project [64]. In addition, it is easy to construct compared to the Chinese model and it is better suited to the variety of climates and soil types compared to the same model. Regarding the advantage of diverse types of soil, this model can be constructed even at the terrain level in cold/temperate or even tropical climate [61,64].

2.2.1.2. Chinese model biodigesters. The Chinese model is simpler and cheaper compared to the Indian. This biodigester operates according to the principle of the hydraulic press. If the accumulation of biogas causes an increase in the internal pressure, the effluent from the fermentation chamber will be forced to the outlet box, and in the opposite direction in case of decompression. The storage of the biogas occurs inside its own structure, which is constituted by a cylindrical chamber for fermentation (masonry made) and an impermeable ceiling. Fig. 9 shows the front view of a Chinese model biodigester [63,65].

However, one of the great obstacles of this technology is the technique for its construction. The work requires skilled labor as the bricks need to be laid without the tendering of the shoring to the chamber where the biomass is digested. In addition, an impermeable coating should insulate the outer and inner walls to prevent cracking or water infiltration. The latter can cause water table contamination if there is

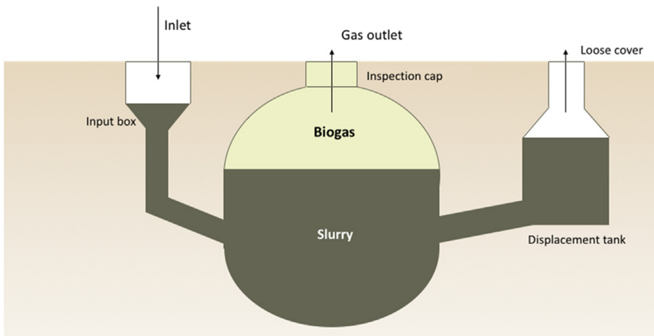

Fig. 9. Chinese model biodigester. Based on [67].

direct contact with the substrate [68]. In this model, it is fundamental to observe the measurements of depth and diameter, which can be difficult in many projects, especially for stony and/or soggy soils [63,65].

2.2.1.3. UASB model biodigester (Upflow Anaerobic Sludge Blanket Reactor). The Upflow Anaerobic Sludge Blanket (UASB), also known as the anaerobic reactor of sludge blanket, is the model generally used for very high biomass concentration. It is the most widespread for sewage and can also be used for the treatment of organic matter present in the municipal and rural waste. This biodigester type is characterized by the effluents upward flow and its sludge blanket. The sludge blanket allows the insoluble organic matter to remain trapped, reducing the organic matter retention time in the biodigester (Fig. 10). The UASB biodigester is mostly used in Brazil [69,70].

2.2.1.4. Covered lagoon biodigesters. This system takes advantage of the low maintenance requirement of a lagoon while capturing biogas under an impermeable cover, as shown in Fig. 11. The first cell of a two-cell lagoon is covered, and the second cell is uncovered. Both cells are needed for the system to operate efficiently. A lagoon is a storage as well as a treatment system; the liquid level on the second cell must rise and fall to create storage, while the level on the first cell remains constant to promote manure breakdown. This model is best suited for industrial and agro-industrial projects due to its versatility and biogas storage ability [71,72].

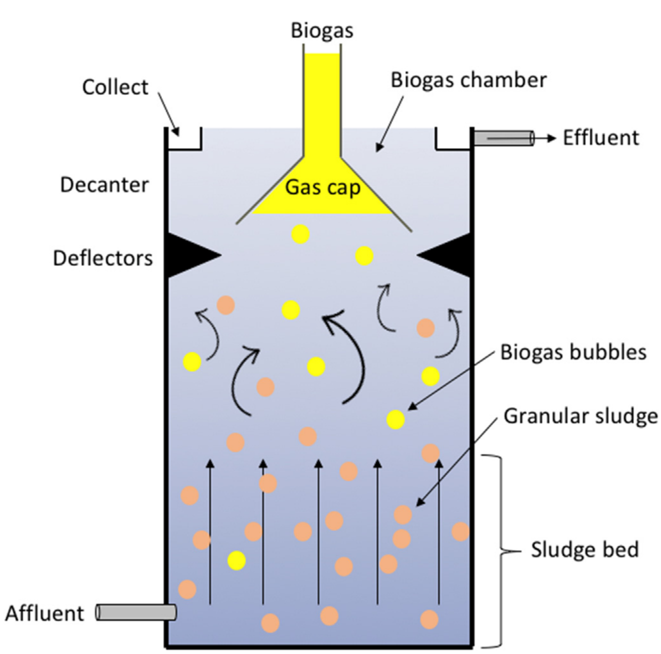

Fig. 10. UASB Biodigester.

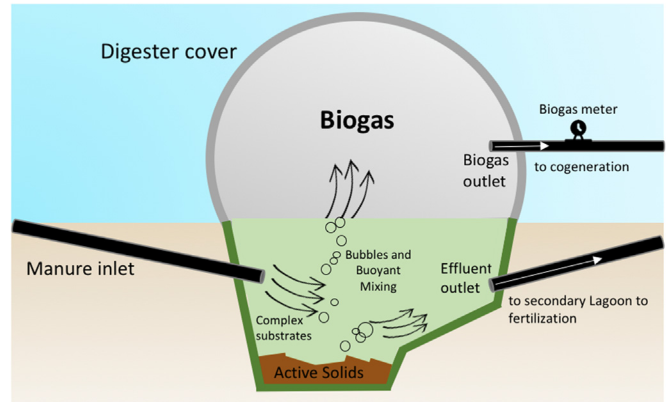

Fig. 11. Lagoon Covered Biodigester.

Although the biodigester removes the organic matter and nutrients part of the waste, it should not be considered as a definitive system of anaerobic treatment of the waste, but as part of a treatment process, and its effluents must be used as an organic fertilizer in properties [12]. Also, the temperature is a key factor in planning a covered lagoon. Warm climates require smaller lagoons and have less variation in seasonal gas production. On the other hand, colder temperatures will reduce methane production [71,72].

In Brazil, the use of Chinese and Indian biodigesters showed a low durability (two years on average), due to the corrosive potential of the sulfuric gas over the structures with ferrous components, from the campanula to the fence wires and other artifacts with iron. Based on this, Brazilian constructions of biogas structures have incorporated the use of concrete and stainless steel, following a European tendency. From the Canadian experience, covered lagoons with plastic tarps have been also used [12,61].

2.3. Comparison amongst technologies for electric power generation

This section presents a comparative analysis of the main alternatives for combined electricity and heat generation using biogas (Table 2), considering the main prime movers used, their capacity, yield, NOx emissions, and limitations (Table 3) [64,68,73].

Gas engines show advantages in their single cycle efficiency value and a very fast startup performance. However, gas turbines demonstrate superior performance under a relatively continuous stable load regime. Comparing gas engines and gas turbines technologies under the same plant load, in single or combined cycle, helps to understand the superior efficiency of the gas engines over operating time [73,74]. On the other hand, microturbines are a relatively new technology for the distributed generation of electricity, whose capacity ranges from 30 to 1000 kW, such as Capstone microturbines. But these prime movers can be paralleled up to 30 MW of power [75]. These modern units are packaged with integrated digital protection, synchronization, and controls; they have high combined heat and power efficiencies and are capable of using multiple fuels [74,75]. Like other technologies, such as fuel cells, wind turbines, and photovoltaic cells, microturbines are generally best suited to relatively small applications and are designed to supply electricity for onsite energy demands and for end users in close proximity to the generation site. Their basic principle comes from open cycle gas turbines, although they present several typical features, such as variable speed, high-speed operation, compact size, simple operability, easy installation, low maintenance, air bearings, low NO_X emissions and usually a regenerator [73,76]. In general, total system efficiencies are about the same for each technology when heat recovery is considered. Microturbines require less scheduled maintenance than reciprocating engines, and this difference should be considered in total

Table 2
Analysis of the main alternatives for combined electricity and heat generation using biogas.
Source:Adapted from [64,68,73].

Alternatives	Advantages	Disadvantages
Internal combustion engines	• Moderate investment cost; • Simple maintenance; • It features quick start, stable operation and is usually quite reliable; • It provides thermal energy at high temperatures; • Mature and widely applied technology for energy generation from biogas, especially in installations with power from 800 kW; • A wide range of stationary motors available in the market, covering a wide range of applications (5 kW up to 5 MW) and operating cycles; • Usually operated with natural gas, but can be adjusted to operate with propane or biogas; • Great energy recovery potential (electric + heat); • Good performance under variable load regime.	• The difficulty of controlling their high emissions; • Relatively low power to weight and power to volume ratios;
Gas turbine	• The high exhaust gases temperature allows the generation of steam at high pressure and high temperature (nearly 480 °C) or the direct application on industrial processes of heating and drying; • In a combined gas turbine and steam cycle, the exhaust gases from the gas turbine feed a boiler that supplies steam for the steam turbine operation, so there are two sources of electric power.	• High acquisition cost • The fuel should be compressed before being supplied to the combustion chamber, what requires a gas compressor. • High operational cost due to the need gas compression; • Consistent quality gas demand;
Microturbines	• Portable and easy-to-modulate (single or multiple turbines) to fit biogas production and local needs; • Compact equipment with few moving parts, thus requiring less care with operation and maintenance; • Low NO_x emissions, usually ten times lower than the best performing internal combustion engines, and also lower than those emitted by flares; • Able to operate with biogas with low methane content (35 or even 30%); • Ability to generate heat and hot water. Standard equipment configuration usually offers the possibility of integration of a hot water generator (~95 °C) using exhaust heat.	• Efficiency lower than internal combustion engines and other types of turbines. Consume about 35% more fuel per kWh generated; • Susceptible to contamination by siloxane. Feeding with landfill biogas usually requires a higher level of pre-treatment than is required by conventional turbines and other forms of electric power generation; • Currently, few low pressure and high-pressure compressors are available to meet microturbine requirements without the need costly adaptations; • Little information is available on the long-term reliability and costs of operation and maintenance of microturbines running with biogas.

lifecycle cost calculations [74,77].

This chapter presented different models of biodigesters used for the production of biogas, as well as the technologies for the conversion of the biogas to electric or thermal energy. However, the existence of technologies alone, do not guarantee efficiency in its application. Local factors are determinant in this context. Thus, it is necessary to verify in practice the incorporation of these technologies in rural properties, the processes and adaptations necessary for the production of biogas, the conversion into electric energy, and the legal requirements for the connection of the electric energy generated by the plant into the state power system. The next chapter aims to elucidate these issues through a case study, by demonstrating the feasibility and application of technologies developed for the production of biogas and electric power generation.

3. Evaluation of the first distributed energy generation mini-power plant from biogas in Brazil

The Colombari farm generator unit is located in a rural property dedicated to swine farming in São Miguel do Iguaçu in the western region of Paraná state (Brazil). The minigeneration unit has a nominal installed capacity of 100 kVA, and is connected to the COPEL power grid, and adopts the compensation scheme established by Normative Resolution no 482/12, as modified by no 687/15 and access regulated by COPEL Technical Standard 905200 [78].

3.1. Minigeneration chronology

In 2006, with the objective of treating biomass waste produced during raising 3000 finishing pigs, it was installed at Colombari farm a biodigester, with a capacity of treating up to 1300 m^3 of waste, a 50 kVA motogenerator set and a monitoring, control and protection panel [27]. At that time, part of the biogas produced was partially flared and the other part was supplied to the motogenerator set to produce electricity aiming only to satisfy the farm demands, without, however, being connected in parallel to utility grid [27].

After the generation system was in operation, an electrical project was developed to allow the parallel connection with utility grid to the following objectives:

- Allow connecting micro generators in distribution power grid point without cause power grid safety requirements violation, in this case, administered by COPEL (Parana Energy Company);
- Eliminate damage risk to the connected rural and homeowner's equipment;
- Respect the characteristics and adjustments of the COPEL distribution system;
- And elaborate the sensitive generator protection system for abnormal operating conditions of the distribution power grid [27].

In January 2008, several advances were made at Colombari farm.

Table 3
Power, yield and NOx emissions of microturbines and other technologies [68,73].

Conversion technology	Installed Power	Power Efficiency (without cogeneration)	Emissions of NOx
Gas engines (Otto Cycle)	30 kW–20 MW	30–40%	< 3000 ppm Engines with low emission: < 250 ppm
Gas turbines (Medium Size)	500 kW–150 MW	20–35%	Mean approx. 35–50 ppm
Microturbines (Small)	30–1000 kW	24–28%	< 9 ppm

COPEL released the operation on an experimental basis, with electricity generation in parallel with the public grid. The performance was considered adequate, making the Distributed Generation technically feasible as a methodology for micro-scale generation [27]. In the same year, ITAIPU created the Renewable Energy Coordination. This coordination was responsible for the Itaipu Renewables Energy Platform, a joint initiative with a number of partners, including COPEL, the Paraná Sanitation Company, LAR cooperative, teaching and research institutions and suppliers of equipment for the electricity sector. In November 2008, COPEL published the Public Call 005/2008 for the purchase of energy in distributed generation, up to 300 kVA per producer, and a total of 3000 kVA, as authorized by ANEEL. As a result of this Public Call, the Colombari farm starts to sell energy surplus [27]. In 2010, the production of pigs increased in Colombari farm and, consequently, the volume of effluent generated as well. Therefore, a new biodigester with a waste capacity of 1000 m^3 was installed, and the motogenerator had a power unit with a capacity of 100 kVA [27].

3.2. Biogas production

The average biogas production, considering all months of the year, for the facility studied was 582.7 m^3/day. To evaluate the performance of biogas production, some parameters should be monitored and analyzed, such as: monitoring the biogas production, the number of confined animals, and physicochemical parameters associate with biogas production per confined animal (total solids - TS and oxygen chemistry demand - OCD) of the biomass added in biodigesters [27,79].

The biogas production as a function of total solids and chemical oxygen demand are important parameters that result in a reliability study of biogas generation potential for the purposes of electric energy production. It is worth noting that this analysis took place in a comparative way with studies already carried out, and the data could serve as parameters for other projects that may want to replicate this experience [79]. Therefore, Table 4 presents the data obtained from November 2010 to May 2011 at the Colombari farm unit, which were used to evaluate the performance of biogas production unit [79].

Table 4 shows indexes of biogas production as a function of the parameters obtained in the physical-chemical analysis and by the confined animal. These indexes are important because they show the performance of the anaerobic biodigestion process in the farm with the use of biodigesters with a hydraulic retention time of 30 days. By knowing the physical-chemical parameters (TS and OCD) of the biomass resulting from the pig rearing process in this property and using the indices shown in Table 4, it is possible to estimate the biogas production potential for purposes of distributed generation in a pig rearing facility.

During laboratory experiments, Orrico [80] encountered a biogas production between 0.542 and 0.625 m^3 $kgTS^{-1}$ for hydraulic holding times of 29 and 36 days, for a tubular biodigester (similar to the Canadian biodigester installed in the Colombari farm) and using swine wastewater (without solid retention). Another tubular biodigester with swine wastewater was evaluated by Feiden [81] and they obtained a biogas production of 0.470 m^3 $kgTS^{-1}$ without agitation of the biodigester and 0.571 m^3 $kgTS^{-1}$ with agitation. In this way, it is possible to conclude that the average of biogas production obtained at Colombari Farm is within the range defined by the authors.

Table 4
Biogas Production Indices at Colombari Farm [68,73].

Month	Animal per day-	Biogas per animal*	Biogas per TS**	Biogas per OCD***
November/10	4400	0.13	0.59	0.61
December/10	4400	0.09	0.36	0.31
January/11	4400	0.15	0.79	0.6
February/11	4400	0.16	0.6	0.69
March/11	4400	0.16	0.62	0.68
April/11	4865	0.11	0.36	0.41
May/11	4865	0.11	0.27	0.4
Average	**4533**	**0.13**	**0.51**	**0.53**

Note: *(m^3biogas. $Animal^{-1}$.day^{-1}); ** (m^3 biogas. Kg TS^{-1}); ***(m^3 biogas.kg OCD^{-1}).

With the biogas production potential estimated, it is possible to determine the daily electricity production, based on the lower calorific value of the gas and also the conversion efficiency of the technology used to convert the chemical energy of the gas into electric energy. From the amount of electric energy produced, it is possible to calculate the avoided emissions by multiplying the energy generated by the emission factor of the Brazilian matrix (Eq. (1)). This factor is determined by the combination of the marginal factors of operation and construction of the Brazilian energy matrix (Eq. (2)), as suggested by the United Nations Framework Convention on Climate Change [82]. It should be noted, however, that only the biogas operation phase is considered in the calculation of emissions. The emission factor of the operation phase of the plant is assumed to be null because it is biogenic and not fossil as proposed by Salomon et al. and Esfandiari et al. [83,84].

$$E_v = E.\ E_f \tag{1}$$

$$E_f = E_{fo}.\ w_o + E_{fc}.\ w_B \tag{2}$$

Where: E_f = CO_2 emission factor for the Brazilian electric matrix (0.390 tCO_2/MWh); w_o and w_B are the weights for the phases of operation and construction, equal to 0.5 [82]; E_{fo} and E_{fc} are the marginal emission factors for construction and operation for the Brazilian electrical matrix in 2016, equal to 0.6226 and 0.1581 tCO_2/MWh, respectively [85].

The amount of CO_2 emissions avoided per capita can be obtained dividing the total carbon dioxide emissions avoided by the population of the city. Thus, with the average annual per capita Brazilian emissions equivalent to 2.1 tCO_2/inhabitants according to the National Energy Balance of 2017, the per capita emission of the city reduced by the construction of the biogas plant can be determined (EPE, 2017).

3.3. Electromechanical conversion and sizing of the electricity generating system in the unit

In the process of electromechanical energy conversion, it is important to know the system design of the motogenerator set to be installed. The electricity generation system is the most important component for the installation of the distributed generation project in the agro-industrial sector with use of the residual biomass. The parameters to be used in the design of the motor generator set are: biogas calorific value (heating value), motor generator efficiency, daily availability of biogas in agro-industrial units and the time of use of the generation plant.

For the design conditions, the average biogas production used was 582.7 $m^3.day^{-1}$. Therefore, knowing the biogas Lower Calorific Value (LCV) [$kWh\ m^{-3}$] and the Daily Production of biogas (DP) [$m^3\ day^{-1}$], it is possible to determine the Theoretical Electricity Production Potential (TEP) [$kWh\ day^{-1}$], through Eq. (3):

$$TEP = LCV*DP = \quad 3,496 \quad [kWh.day^1] \tag{3}$$

The biogas LCV is directly related to its methane content of the biogas, and inversely related to carbon dioxide content, that is, the higher carbon dioxide concentration, the lower the caloric value. Thus, the biogas production process must have a favorable condition for the higher production of methane and lower production of carbon dioxide, in order to increase its LCV. The technical potential of electricity production (TEP) is determined to take into account the global conversion efficiency (η) in the thermal machines (generator set, gas microturbine, etc.).

For using biogas as fuel, either in engines, turbines or micro-turbines, it is necessary to determine the fuel flow demand, chemical composition, and heat power, parameters which determine the real potential of the generation of electricity. There are two basic types of engines which should be executed with the biogas: those with Otto cycle and those with Diesel cycle [86]. According to Nishimura [87], the Otto Cycle internal combustion engine requires few adjustments to operate with biogas as fuel. When compared to the Diesel Cycle, this one is more robust and cheaper than Otto Cycle. However, for using biogas in diesel engines, it must undergo modifications in such a way that the engine is practically converted into an Otto engine. Therefore, the Otto Cycle use is more common for small sizes (50–100 kW) [88,89].

The Otto cycle engine inflames the fuel with a spark-ignition and it generally uses volatile fuels, like gas. Theoretically, the Otto cycle engine must be more efficient than the Diesel cycle engine. Due to the fact that the comprehension rate inhibits the efficiency of the Otto cycle engine, a Diesel cycle engine is considered more efficient in the practice. The Diesel cycle engines inflame the fuel by means of its compression. In a correct combination of the pressure and temperature, the fuels would burn themselves. Therefore, the engine must be projected for the destined fuel, with the right temperature and pressure. Concerning the ignition commanded by pure gas, it is considered that most of the Otto cycle engines which use gas, currently may be easily modified for the functioning with natural gas, propane, methane compressed [88,89]. For the Otto Cycle engines with the generation group attached the average efficiency assumed is 25% and this value depends on the adaptation of the Otto cycle engine for biogas operation and the injection system adapted from the natural gas engine [89,90]. The Electricity Production Technical Potential (EPTP) [kWh/day] can be defined as shown in Eq. (4):

$$EPTP = \frac{TEP^{*}\eta}{100} = 874[kWh.day^{-1}] \tag{4}$$

In this way, the Electric Power (EP) of the generation plant can be obtained through Eq. (5):

$$EP = \frac{EPTP}{HO.\cos\varphi} = 109.25 \quad [kVA] \tag{5}$$

where, EP is the Electric Power of the generation plant [kVA], HO is the number of hours of operation of the generator set [h] and $\cos\varphi$ is the power factor, which varies from 0.8 to 1.0. Thus, the data of the generation system at Colombari farm are summarized in Table 5.

Analyzing the data from Table 5 it is possible to observe that a motor-generator of 100 kVA is enough for the electric Power required for the system for a unit power factor. Although the electric power is a little bit superior, there are several variables that can reduce the gas production or its lower calorific value. The generator set will operate according to the biogas availability in the biodigester, being scaled to operate approximately eight hours per day.

Combining the marginal factors of construction and operation for the Brazilian electrical matrix with the energy produced annually by the biogas plant, the CO_2 emissions avoided can be calculated (See Eqs. (1) and (2)). For the city of São Miguel do Iguaçu an amount of 124.41 tCO_2 was obtained, equivalent to a reduction of 4.53 $kgCO_2$/inhabitants per year. According to the Carbon Neutralization Techniques by planting trees [91], is possible to compare the total amount of CO_2 emissions avoided with the number of trees that would be needed to neutralize this value. This occurs by sequestering carbon dioxide from the atmosphere, which is fixed in the plant biomass to be consumed. The average of carbon sequestration by one tree is 15.6 $kgCO_2$/year [91], equivalent in this case using a biogas plant, to avoid reforesting an area with around 7975 trees [91].

In addition, there are other advantages associated with the biogas plant, not only to increase the supply of alternative sources of electric energy in the Brazilian electrical matrix but also in the treatment of waste produced by animals or municipal liquid effluents. Therefore, if the biogas plant is economically viable, in addition to the economic benefit, dealing with an environmental liability helps to improve the quality of the environment, reducing problems such as improper waste disposal in the soil, contamination of groundwater by animal waste, eutrophication of water bodies, among other environmental impacts.

Table 5
Sizing of the electricity generation system at Colombari farm.

Parameters	Nomenclature	Value
Daily Production of biogas [m^3 day^{-1}]	DP	582.7
Lower Calorific Value [kWh m^{-3}]	LCV	6
Theoretical Electricity Production Potential [kWh day^{-1}]	TEP	3496
Efficiency of the generating engine	η	25
Electricity Production Technical Potential [kWh day^{-1}]	EPTP	874
Number of Hours of Operation	HO	8
Power factor	$cos\varphi$	1
Electric Power [kVA]	EP	109.25

4. Future perspectives

Biogas is a fuel with all the technical and economic conditions to be exploited in Brazil. With the expansion and growth of this category of energy reuse, it is possible to stimulate the technological development and the industrial sector specialized in biodigesters, motors, converters, control units and other equipment. The expected positive consequences in the productive chain involve the increase of employment and income.

Besides the perspective on the chain development, the biogas has others roles to play for Brazil. The case of biogas production from solid urban waste, which represents more than 95% of the total of the national biogas production as seen in Table 1, contributes to the implementation of the National Solid Waste Policy [92]. This Policy is a Brazilian National effort to the protection of public health, environmental quality, and sustainable development. At the macro level, with the biogas production and its use in the electricity generation, the consumption of fossil fuels can be reduced, as well as the amount of CO_2 emissions. The promotion of biogas production is also a mechanism to reach Brazil's Intended Nationally Determined Contributions (NDCs) assumed in the Paris Agreement in 2015.

The prospects of the biogas production at the farm level are even promising. Economically, it increases the income of the activity, since the earmarked resources for the payment of the energy bill will be lower or zero. These small power generation plants known as distributed micro or minigeneration can perform the electricity compensation through credits that are valid for up to 60 months, supported by the Normative Resolution from ANEEL [78]. By this Resolution, distributed microgeneration is characterized by generating electricity with an installed power less than or equal to 75 kW, while the distributed minigeneration refers to power plants with installed power above 75 kW and less than or equal to 3 MW for water sources, or 5 MW for sources such as biogas. Looking through an environmental perspective, the livestock activity in Brazil generates a large volume of wastewater, especially the swine production. An anaerobic wastewater treatment plant can treat the large volume of residues generated by the activity. The correct disposal of the waste reduces the contamination of rivers and groundwater while it also benefits the rural and urban population by reducing the odor of the activity. The last scenario involves the stabilization and quality of rural electricity distribution. It is common for Brazilian rural areas to experience power outages or grid instabilities. The slightest incident in a given location of the grid might disconnect the entire energy line for hours, directly affecting the agricultural and livestock sector. In some activities, such as poultry farming, energy is vital to the survival of the animals and a power outage can mean thousands of dead animals. The local production of energy by biogas plants and the distribution arrangement on microgrids might have the potential to stabilize rural energy distribution and to ensure sufficient energy for future investments.

Even though the benefits of the biogas production and its linkage to energy generation are technically validated in the researches and have already been applied at rural and urban areas, some gaps need to be overcome. Currently, the biggest obstacle is the lack of public policies and regulations that subsidize these projects to make economically viable. In this case, it is important that the government encourage policies for the implementation of biogas projects, such as the development of technologies to reduce biogas generation costs and also national and international partnerships for research to provide equipment and support. In addition, it is fundamental to have human resources training and capacity to provide technical assistance to producers, as well as enhance technical and scientific knowledge through courses, seminars, workshops on the use of biogas. Brazil has been implementing the first initiatives through the creation of national and international programs such as RenovaBio, Probiogás, CIBiogás and Abiogás. The Biogas Map is one of the initiatives to encourage the sector and show the feasibility of biogas projects.

The study carried out in this work is extremely relevant and important for the development of the research of this renewable source of energy for electricity production in the Brazilian market. Thus, it was shown the general panorama of electric energy production in Brazil from biogas and a case study of Colombari farm. These studies could be used for other biogas plants in Brazil or in other regions of the world, contributing to the economic and regional development, environment and research. Future work intends to carry out an economic study of biogas plants, observing financial indicators such as Net Present Value and Return on Investment to analyze how to increase the economic viability of biogas energy projects.

5. Conclusions

This review presents the Brazilian market of distributed biogas generation, through the technologies for biogas production, the scenario of electric distributed generation in Brazil and a case study of the first Biogas Generation Plant installed in the state of Paraná. Currently, the renewable energy from biogas represents a small share of the Brazilian electricity matrix, accounting for approximately 0.08% of the total. In addition, biogas from animal waste, which was the main study of this work, has a share of 1.73% only, within the total amount of electricity from the biogas. The predominant biogas source in Brazil is still from urban solid waste, with a greater electricity production compared to animal and agro-industrial wastes, which corresponds to 96.77% of the electricity produced from biogas. Although the production is not high, the study of Colombari farm inserted in the Brazilian electric power matrix made it possible to observe the significant impact in reducing the emission of carbon dioxide in the atmosphere. Another important factor is the correct disposal of effluents and organic waste (residual biomass), reducing the organic matter amount disposed into the rivers, which highly contributes to the solution of environmental problems.

To use the biogas generated in the process, it is necessary to acquire better knowledge through the parameters and variables involved. As it was observed in the case study, the Colombari farm can produce to the grid approximately 100 kVA power for eight hours a day. Finally, it increases the reliability of the system with the diversification of the energy matrix, expanding the power generation and the efficiency with the reuse of the organic matter for electricity production.

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