Chapter

Biogas Power Energy Production from a Life Cycle Thinking

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Abstract

The purpose of this chapter is to present a generalized model for the construction of inventories for the production of electricity through biogas. This general framework can be adjusted to any power plant that uses biogas, since it complies with the main material and energy balances. This chapter describes the main technologies used in biogas power energy production, separating them into five main subsystems that integrate the general life cycle inventory, as well as the inputs and outputs considered in the development of the inventories. The life cycle assessment (LCA) of two types of plants is presented as study cases: (i) the biogas power energy generation with organic waste in landfills as substrate and (ii) the biogas power energy generation using dairy cattle manure as substrate. Both systems, in addition to using different types of substrate, present differences in their substages. It is concluded that the generation of studies of life cycle analysis of technologies facilitates decision makers, producers, and government agencies to develop and identify areas of opportunity from life cycle thinking.

Keywords: biogas, emissions, smart industry, sustainable energy, cleaner energies

1. Introduction

Energy is a critical factor for global decision-making. The energy supply is not only an important support in the daily anthropogenic activities, but also an important macroeconomic element [1]. Månsson [2] suggests a relationship between the energy sector of a country and the adaptation to changes, such as environmental degradation and the food price increase. This adaptation is carried out in a political, economical, and social context. Consequently, the energy topic has increased its relevance in international relations and dependencies. According to Overland [3], energy is a sensitive factor in globalization.

The development and the recent social growth are highly dependent on nonrenewable energies. This dependency has several disadvantages. Nonrenewable energies (NRE) are directly associated with climate change [4]. Since the last century, the atmospheric concentrations of CO_2 have increased from ~290 to 400 ppm in 2015 [5]. This period is related to an exponential increase in the energy demand. Another disadvantage is the resources depletion. Oil, for example, demands gradually more investment for few products. According to the Mexican government reports, the investment in oil extraction and exploration has increased 140% between 2004 and 2012; meanwhile, 30% less of the daily production initially perceived was obtained [6]. In general, both climate change and the resources depletion are issues of great importance at present [7]. This panorama incentivizes the investment for economic, scientific, and technological development for alternative and renewable energies.

Nowadays, several potential renewable energy sources are known. Its usage depends on its accessibility and transformation capacity. The energy obtained from biological sources, such as wood, crop residues, municipal waste, or even organic industrial waste, is called biomass energy [8]. This is widely used for heating and cooking activities [9] and is one of the oldest renewable energies. Biomass can be harnessed in several ways; energy sources can be obtained as many products, such as hydrogen, ethanol, methanol, and methane for transformation into mechanical energy and electricity. The biomass use comes with disadvantages. Overexploitation of biomass could damage natural areas by promoting the creation of monocrops to meet the energy demand [10]. However, the energy obtained from biomass waste could be a useful renewable energy source.

A product derived from the biomass fermentation is the biogas. It is obtained by a bacterial degradation denominated anaerobic digestion (DA) [11]. It is commonly used to obtain two main products: biogas to produce energy and digestate used for agricultural soil treatment.

The production of energy through biogas is a key element for future global projections. In Mexico, the potential for power energy generation through biogas is between 652 and 912 MW [6]. The use of renewable resources needs to be developed at an accelerated growth rate to meet global energy demand [12]. Its implementation must be successful too, oriented toward sustainability [13]. An applicable methodology to evaluate by this approach is the life cycle assessment (LCA).

Currently, the LCA has been applied to various energy production systems. The adoption of technologies such as biogas is generally promoted by environmental issues [14], specifically for waste disposal. The LCA methodology is an important tool in the use and implementation of anaerobic digestion for the generation and use of both biogas and soil improvers. Harder et al. [15] conducted a study of wastewater sludge treatment and integrated a quantitative microbial risk analysis into the LCA results. Dressler et al. [16] and Van Stappen et al. [17] carried out LCA studies of biogas production, the first about maize in three different areas of Germany; the second is about the installation of a farm biogas plant. Based on a sequential approach, both studies conclude on the importance of carrying out regional inventories for their application in decision-making. In China, Xu et al. [18] studied the generation of biogas from food waste. They found that the electrical consumption and transport of raw materials comes with the highest potential impacts. Moreover, Hijazi et al. in Germany analyzed 15 different biogas systems and found from life cycle thinking that the type of raw material is a key factor in environmental impacts. Furthermore, the spatial distribution of the plant and the management of by-products presented the highest environmental impacts. On the other hand, Huttunen et al. [14] identified that the use of biogas and the final use of digestate are the most critical points in the production of biogas in Finland. The construction of local inventories is a necessity to improve the LCA studies quality.

LCA is a useful tool for sustainability assessment in biogas systems. There are several studies of LCA in biogas. A general framework for biogas production has been established by other authors in independent studies. However, the recent studies focus on particular stage improvements or new technologies implementation.

In order to facilitate the construction of biogas power generation inventories, a general framework is desirable. This chapter presents the life cycle analysis of the generation of electrical energy by biogas, dividing the biogas power generation in individual subsystems. Two scenarios were considered for the elaboration of the ACV study, the use of biogas from the dairy corral excreta and the one from the municipal sanitary landfill.

2. A biogas background

Biogas is produced by anaerobic bacteria that degrade organic matter in four general stages: hydrolysis, acidification, acetic acid production, and methane production. The gas phase product of anaerobic digestion is named biogas and its yield depends significantly on the substrate (raw material). Biogas is composed by a mixture of 50–75% methane, 25–50% carbon dioxide, and 2–8% other gases (nitrogen, oxygen, hydrogen sulfide, among others). The percentage of methane in the biogas mixture is the main component for its use as an energy source; this also depends on the substrate that is used. **Table 1** shows the potential production of methane with different types of substrate, as well as its yield.

Before converting biogas into electricity by motor generators, the biogas must be purified by a desulfurization and drying process [11].

The requirements of the biogas quality depend on its different applications. In general, the costs of biogas purification are associated with the technology used and the location of the biodigestion system [20]. The choice of the most appropriate technology for the removal processes will depend on the use of this energy, as well as the compounds present in the biogas.

The toxic effect of H_2S, which is a colorless, flammable gas, has been documented, at levels of 0–5 ppm in the air, it can be easily detected; at concentrations higher than 10 ppm, it can affect human health, and at 600 ppm, it can cause death [21]. This gas is in the top five of pollutant compounds by Environment Canada's National Pollutant Release Inventory [22]. The main problems in the use of biogas, due to high concentrations of this gas, are the corrosion that damages the engines and the production of sulfur oxides from their combustion, whose emissions are subject to international regulations [23]. Therefore, desulphurization of biogas and its purification are necessary to increase the possible applications of this energy [24]. The main removal technologies for this compound are presented in **Table 2**.

The design of an optimal digester depends mainly on the characteristics of the substrate, as well as the amount of dissolved, volatile solids, biodegradability,

Substrate type	C:N ratio	Methane yield (m^3 CH_4/kg VS)	Methane production (m^3 CH_4/m^3)
Pig manure (solid)	7	0.30	48.0
Cattle manure (solid)	13	0.2	32.0
Poultry droppings (solid)	7	0.30	48.0
Garden wastes	125	0.20–0.50	NR
Fruit wastes	35	0.25–0.50	NR
Whey (from industry)	NR	0.33	0.15

NR = Not reported.

Table 1.
Biomass characteristics for biogas production [19].

Method	Advantages	Disadvantages
Biological with O_2/air, (by filter/ scrubber, /digestor)	Low investment and operating costs: electricity and calorific demand. It does not require any chemical products or additional equipment. Easy operation and maintenance.	The H_2S concentration remains high. The O_2/N_2 excess complicates an additional cleaning An over The overload of air produces an explosive mixture
$FeCl_3/FeCl_2/FeSO_4$, (in digestors)	Low investment cost: storage tank and dosification pump. Low heat and electricity demand. Easy operation and maintenance. Compact technique. Air absence in biogas.	Low efficiency. High operation costs (Iron salt). Changes in pH and temperature are not beneficial for the digestion processes. Difficulty in dosing.
Bed of $Fe_2O_3/Fe(OH)_3$ Steel wool covered with rust Wood chips or impregnated balls	High removing efficiency >99% Low investment cost	Water sensibility High operating costs. Exothermic regeneration: Wood chips ignition risks The reaction surface is reduced for each cycle. The dust released could be toxic.
Absorption by water	Low costs when there is water availability (nonregenerative) CO_2 is removed too.	High operation costs: high pressure, cold temperature. Difficult technique It could be presented obstructions in the absorption column.
Chemical absorption NaOH, $FeCl_3$	Low electricity demand Lower volume, less pumping, smaller vessels (compared to water absorption) low CH_4 loss.	High investment and operating costs. Difficult technique. Nonregenerative.
Chemical absorption $Fe(OH)_3$,Fe-EDTA	High efficiency in removing: 95–100% Low operation costs Small volume required Regenerative Low CH_4 losses	Difficult technique Regeneration by oxygen CO_2/H_2CO_3 (using EDTA) causes precipitation Thiosulphates accumulation
Membrane	Removing >98% The CO_2 is also eliminated	High maintenance and operation costs Complex
Biological filter	High remotion rate > 97% Low operating costs	An additional H_2S treatment is required The O_2/N_2 excess dificult an aditional cleaning
Adsorption by activated coal.	High efficiency High purifying rate Low operation temperature Compact technique High load capacity	High operating and investment costs CH_4 losses H_2O and O_2 are necessary to remove H_2S H_2O could occupate the H_2S role Regeneration at 450°C

Table 2.
Types of biogas purification technologies [25].

density, buoyancy of the solids and particle size [26]. Bioreactors can be classified as dry and wet. Some common configurations are: (i) dry batch reactors, (ii) continuously stirred tank reactors, and (iii) dry continuous reactors.

Technological advances have focused on new configurations, variants and modifications of conventional biodigesters. The anaerobic membrane reactors (AnMBR) have attracted attention in the field of research. This technology consists in the use of a membrane for the separation of solids and liquids inside the reactor, facilitating the handling of the effluent [27]. The membranes can be of different materials, in general they can be polymeric, metallic and ceramic, each one with its particular advantages [28]. The configuration of the use of these membranes varies according to the design of the reactor and the particular needs, from internal membranes, to membranes that operate by vacuum [29].

The production of electricity through biogas has been a notable increase in recent years. It is known that only in the European Union, the energy generated by biogas increased to 20,467.20 GWh in the period 2010–2013 [30]. Likewise, in other countries it has been found feasible to generate electricity through biogas. Arshad [31] carried out an economic study of the feasibility of generating energy using biogas from poultry residues. In his study he lists AD technology with a high potential to reduce Pakistan's local power deficit. Likewise, there are studies related to the application of improvements in order to increase the efficiency and feasibility of studies. Markou [32] presents an economic study where he uses the heat energy generated by the production of energy with the incorporation of greenhouses in the biogas plant, and they conclude that this modification contributes favorably from the economic point of view. In general, energy demand, as well as the need to search for new technologies, has favored the research and development of DA technology.

3. Biogas in the life cycle inventory process

The process of generating biogas, as well as its consecutive stages for the production of electrical energy, consists of several stages. **Figure 1** mentions the components for the design of a biogas utilization plant. Each of the stages can have a different design depending on the needs and the type of substrate to be fermented.

The development of the life cycle assessment can be separated into five main stages: (i) the collection of the substrate and its storage, (ii) pretreatment of the

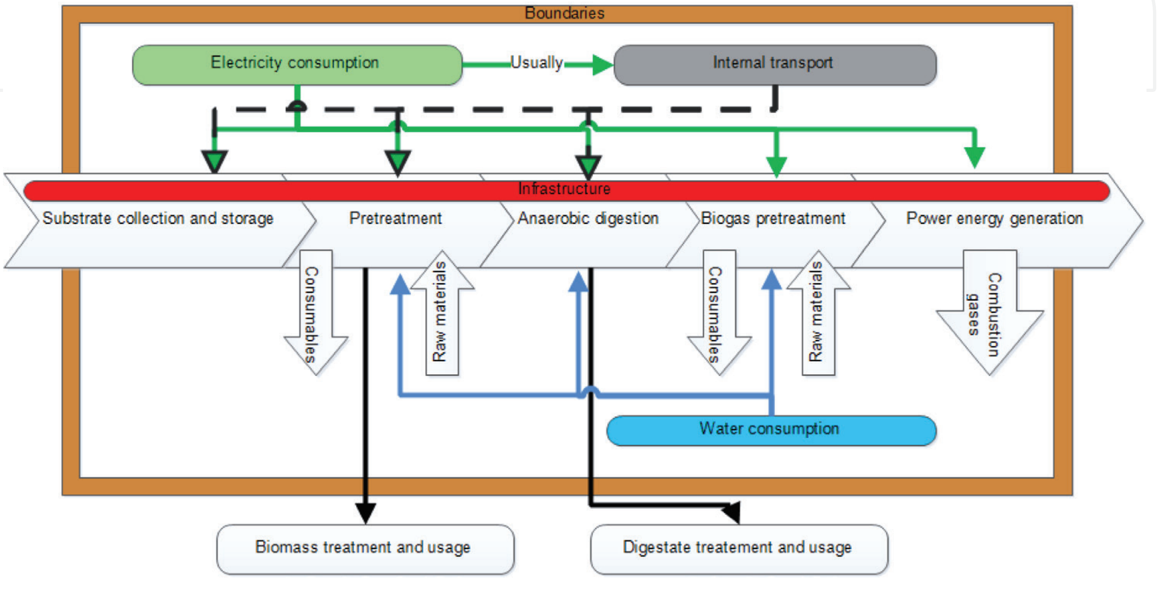

Figure 1.
Boundary limits for a biogas power plant life cycle inventory.

substrate, (iii) anaerobic digestion, (iv) pretreatment of biogas, and (v) generation of electric power. **Figure 1** shows a gate-to-gate flow diagram of the inputs and outputs of each of the stages of energy generation using biogas. The limits in **Figure 1** indicate the use of biomass and digestate in the pretreatment and anaerobic digestion stages, respectively, as well as outside the process of producing electricity through biogas. These processes can be considered by-products, which would allow them to be included within the limits as outputs to the technosphere. However, depending on the activities of the producers and the type of substrate, this digestate can be considered as waste. For a general analysis focused on the generation of electrical energy, these processes are considered as beside to the generation of energy, for the present work.

The essential part to be considered in the life cycle inventory (LCI) in a biogas plant is the infrastructure. Da Costa et al., mentioned infrastructure as part of the processes to consider in carbon dioxide emissions. Studies catalog the generation of emissions by infrastructure as low [33]. However, the contribution percentage of this system depends on the useful life of the plant because they are not constant emissions [32]. The maintenance, the configuration of the processes, and the type of bioreactor among other factors influence the useful life of the plant.

The first stage in the balance of matter and energy is the collection and storage of the substrate. It has been found that the variety of substrates used is wide. The types of substrate most used are: animal manure, agricultural residues, agroindustrial waste and even municipal organic waste [34]. These residues vary in composition, condition, density, as well as the type of collection and storage. In **Figure 1**, electricity was considered as an entrance; however, transportation plays a key role in this stage. Usually, substrates such as municipal waste are confined in landfills. The sealing of the cell favors anaerobic microbial consortiums that allow the generation of biogas. The same storage system fulfills the function of bioreactor, suppressing the pretreatment stage. For cases such as the use of animal waste, a more complex collection and storage system is necessary. These types of plants are usually of small or medium scale and are located near the source of the substrate. The collection of the substrate can be carried out by tractors or cargo vehicles. Also, transport and storage depend on the logistics, as well as the source of the substrate. The main factors to consider in this stage are the use of land and the emissions generated by transportation.

As mentioned in Section 2, the pretreatment stage varies according to the technology used. The access and availability of water are essential for the balance of material in this process. The relationship between the percentage of water and the content of solids in the substrate influences the yield and production of biogas [35]. Veluchamy and Kalamdhad [36] considered in their study a range of 80–85% humidity for an optimal methane yield in the DA of lignocellulosic substrate. Good practices mainly influence this stage and the use of water. Likewise, the electrical energy consumed is a key factor in this stage depending on the separation technology. Another important outlet is the residual organic matter. As already mentioned, this biomass can be considered as waste or as a byproduct depending on the use. This chapter focuses mainly on the generation of biogas and electricity. So the use of biomass and digestate (in the DA stage) were not considered.

The DA is the main stage of the biogas utilization plant. In addition to the infrastructure, it is necessary to consider the inputs and outputs in the monitoring and control of the parameters. Anaerobic digestion occurs in three main levels: psychrophilic (<25°C), mesophilic (25–45°C), and thermophilic (>75°C) conditions. Usually, digesters work at mesophilic conditions [34]. The energy consumption depends mainly on the temperature difference between the environment and the level of thermal conditions in which the plant works. Occasionally, producers opt for psychrophilic conditions due to the climatic conditions of the region [37]. Likewise, other parameters such as pH, micronutrients, and ammonia should be considered in the balance of inputs and outputs if necessary.

The pretreatment stage of the biogas is necessary for an optimal operation in the generation of electrical energy. As mentioned in Section 2, there are various techniques for removing unwanted components. The LCI depends on consumed inputs and the waste generated by the processes. So, the consumption of electricity and other energy inputs must also be considered in the balance.

The electric power generation stage is a key factor, not only for the construction of the LCI, but also for the design of the plant. The generation of electrical energy depends mainly on the technology used. It also depends on the composition of the biogas used. In this stage, the generation-consumption balance for the knowledge of net energy is crucial. The understanding of the energy flows consumed throughout the plant, compared with the energy generated, is critical for the optimization of the plant [38].

The five stages mentioned in **Figure 1** are the general scheme of an LCI for the generation of electric power. However, the configuration and stages may vary depending on the needs and the type of substrate. A system that uses urban solid waste sometimes lacks a pretreatment stage for the substrate. Also the collection methods may vary or belong to other linked operations. For example, the collection of animal excreta is a process also considered as cleaning stables on a farm. If the plant is in production, the collection is part of the cleaning system. The main outputs of the process are the residuals of the pretreatment stage of the substrate, the biogas, the digestate emitted by the anaerobic digestion and the emissions of combustion gases by the generation of electrical energy.

The development of the LCA is a comprehensive process. The form of construction of the inventory is explained in ISO 14044 [39]. **Figure 1** shows a gate-to-gate diagram of the system boundaries. However, the inclusion of other subprocesses should be considered according to the boundary conditions of the particular study.

4. Biogas and impact categories

In accordance with ISO 14040 [40], the life cycle impact assessment (LCIA) is intended to assess how significant the potential impacts of LCI emissions are. Generally, this evaluation is carried out through impact categories according to the emissions generated by the system. Currently, there are databases with impact categories already established. Some of the most used databases are ReCiPe, CML 2001, IMPACT 2002+, and IPCC 2013, in which the carbon footprint is obtained [41].

For a gate-to-gate study like the one shown in **Figure 2**, generally, the main emissions are air and water. However, depending on the system to be studied, additional emissions to the soil can be considered. For example, sometimes the digestate produced by the DA with a subsequent treatment can be used as a soil improver. However, if this is not carried out, it is possible to consider it as emission to the ground. This happens with the treatment and use of biomass in general. The consideration of these emissions within the limits of the system depends on the objective of the LCA.

The emissions to the air are carried out as a result of the generation of electrical energy by combustion, mainly. The exhaust gas mixture contains CO_2, CO, and H_2O, and other pollutant compounds such as SOx and NOx. The main impact of these emissions is the potential global warming. However, some of these compounds can generate from air toxicity to carcinogenicity.

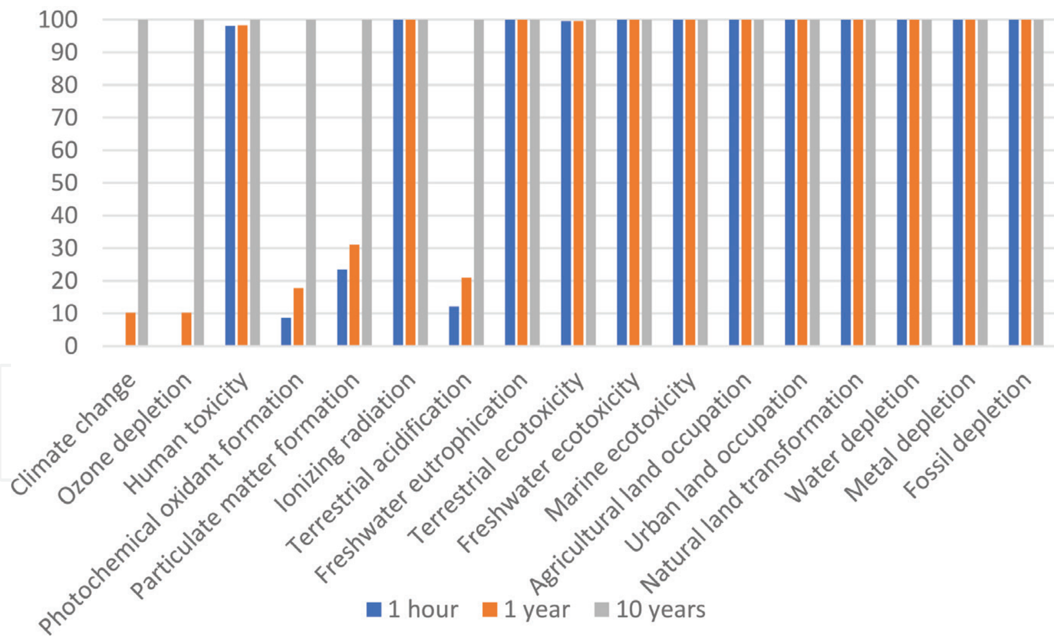

Figure 2.
Life cycle impact assessment of the landfill biogas power generation.

Regarding emissions to water, there is a considerable consumption of water, which is dependent on the technology and the size of the plant. As already mentioned, the composition of the digestate may contain micronutrients, which can be used for soil improvement. However, the emission into water of these compounds derived from phosphorus and nitrogen can cause eutrophication in water. Moreover, the emission of elements such as arsenic, lead, magnesium, etc. could contribute to the freshwater toxicity. It is advisable to carry out chemical analysis of the digestate at the exit of the system and in case of being disposed to bodies of water, consider it in the hydric balance.

The impact categories were selected based on the characterized emissions. For a standard biogas power plant, it is recommended to chose impact categories related to air toxicity and water contamination.

5. Study cases

In this section, two studies are presented. The first study case presents power generation from landfill organic matter biogas. The second study case presents the power energy generation from dairy manure biogas. Both studies are common examples of biogas-producing substrates.

5.1 Biogas from landfill

The electric power generation plant is located in the cd. Juárez, Chihuahua Landfill, road N °45, Juárez-Chihuahua (coordinates: 31° 33′15 "N 106 ° 29'33" W). The usage of different functional units allows to assess the sensibility of a system. For this study case, three separated periods of time were selected: (i) the generation of electricity from biogas during 1 hour of production, (ii) the annual production of electricity, and (iii) the generation of electricity for 10 years of production. Most of the inputs-outputs diagrams increase their scores linearly. However, it does not mean that the impact categories replicate this behavior.

The life cycle inventory is shown in **Table 3**. Inventories of the Ecoinvent v3.3 database were taken for the infrastructure of the plant [41]. It was considered a land use of 25,949 m^2. Furthermore, four generators with a generation capacity of 1230 kW of electricity were considered. These quantities were defined with the scale of the real power plant; however, the inventories were obtained from the Ecoinvent database. The construction of the plant was not considered due to the lack of information access. On the other hand, the air emissions provided by the producers were considered. The landfill biogas is generated by the anaerobic degradation of the organic matter. This process is carried out without any parameter control inside the landfill. For that reason, both biogas production and consumption is not considered for the study.

Products	**1 hour**	**1 year**	**10 years**	***Unit***
Functional unit	3296	2.89E+07	2.89E+08	kWh
Materials/fuels				
Infraestructura-BiogasJuarez/JRZ/MX	1	1	1	p
Emissions to air				
Carbon dioxide	2040	1.79E+07	1.79E+08	kg
Sulfur dioxide	2.79E-01	2.44E+03	2.44E+04	kg
Water	2.52E+02	2.21E+06	2.21E+07	kg
Ethane, 1,1,2,2-tetrachloro-	9.63E-05	8.43E-01	8.43E+00	kg
Ethane, 1,1-dichloro-	3.37E-04	2.95E+00	2.95E+01	kg
Ethene, 1,1-dichloro-	3.85E-04	3.37E+00	3.37E+01	kg
Ethane, 1,2-dichloro-	1.64E-02	1.43E+02	1.43E+03	kg
Benzene, 1,2,4-trimethyl-	1.01E-02	8.81E+01	8.81E+02	kg
Benzene, 1,2,3-trimethyl-	7.99E-03	7.00E+01	7.00E+02	kg
Benzene	2.91E-02	2.55E+02	2.55E+03	kg
Ethane, chloro-	9.63E-04	8.43E+00	8.43E+01	kg
Ethene, dichloro- (cis)	2.60E-03	2.28E+01	2.28E+02	kg
Methane, dichloro-, HCC-30	3.47E-03	3.04E+01	3.04E+02	kg
Benzene, ethyl-	5.94E-02	5.20E+02	5.20E+03	kg
m-Xylene	1.07E-01	9.38E+02	9.38E+03	kg
o-Xylene	4.94E-02	4.33E+02	4.33E+03	kg
Styrene	2.47E-02	2.17E+02	2.17E+03	kg
Ethene, tetrachloro-	1.61E-02	1.41E+02	1.41E+03	kg
Methane, tetrachloro-, CFC-10	7.70E-04	6.75E+00	6.75E+01	kg
Toluene	1.81E-01	1.59E+03	1.59E+04	kg
Ethane, 1,2-dichloro-	9.63E-05	8.43E-01	8.43E+00	kg
Ethene, trichloro-	5.68E-03	4.98E+01	4.98E+02	kg
alpha-Pinene	1.61E+00	1.41E+04	1.41E+05	kg
Limonene	6.58E+00	5.76E+04	5.76E+05	kg
P-cymene	8.13E-03	7.13E+01	7.13E+02	kg
Octamethyltetrasiloxane	1.29E-01	1.13E+03	1.13E+04	kg
Phenyltrichlorosilane	2.26E-02	2.26E-02	2.26E-02	kg

Table 3.
Life cycle inventory for each functional unit in the landfill biogas power plant.

The characterization for the life cycle impact assessment and the scenario comparison were calculated using SimaPro v8.5.2. **Table 4** and **Figure 2** show the results of the life cycle impact assessment of electric power generation in the Juarez biogas power plant. It can be seen in **Table 4**, a high score of emission equivalents in climate change and human toxicity categories. This is mainly due to the emissions of greenhouse gases and pollutants generated in combustion. On the other hand, emissions in both categories of human toxicity and marine eutrophication have indirect contribution like the equipment manufacture and the infrastructure.

Figure 2 shows the comparison of the potential impacts in the selected functional units. It can be seen that according to the increase of the time in the functional unit, the most sensitive categories scores are: climate change, ozone depletion, photochemical oxidation, particulate matter formation, and terrestrial acidification, which are mainly associated with air emissions. The results show a high sensitivity of gas emissions to the generation of electrical energy through biogas from landfill.

Moreover, the impact categories associated with soil such as terrestrial ecotoxicity, ionizing radiation, freshwater ecotoxicity, marine ecotoxicity, etc. (**Figure 2**) remain constant with increase in time in the functional unit. It is because of the secondary inventories, which are linked to the infrastructure and the manufacture of the power generators, whereby they are associated to indirect emissions.

According to **Figure 2**, air emissions are highly sensitive compared to other emissions. It is because of the biogas combustion caused by the power generation. Additionally, there are many volatile compounds generated with biogas produced in the landfill.

Impact category	Unit	1 hour	1 year	10 years
Climate change	kg CO_2 eq	4.53E+05	1.83E+07	1.79E+08
Ozone depletion	kg CFC-11 eq	1.32E-01	5.06E+00	4.94E+01
Human toxicity	kg 1,4-DB eq	3.07E+07	3.07E+07	3.13E+07
Photochemical oxidant formation	kg NMVOC	5.33E+03	1.09E+04	6.15E+04
Particulate matter formation	kg PM10 eq	1.50E+03	1.98E+03	6.38E+03
Ionizing radiation	kg U235 eq	8.87E+04	8.87E+04	8.87E+04
Terrestrial acidification	kg SO_2 eq	3.38E+03	5.82E+03	2.78E+04
Freshwater eutrophication	kg P eq	4.26E+02	4.26E+02	4.26E+02
Marine eutrophication	kg N eq	1.10E+03	1.10E+03	1.10E+03
Terrestrial ecotoxicity	kg 1,4-DB eq	1.37E+03	1.37E+03	1.37E+03
Freshwater ecotoxicity	kg 1,4-DB eq	9.64E+03	9.64E+03	9.64E+03
Agricultural land occupation	m^2a	4.68E+03	4.68E+03	4.68E+03
Urban land occupation	m^2a	3.13E+04	3.13E+04	3.13E+04
Natural land transformation	m^2	2.27E+02	2.27E+02	2.27E+02
Water depletion	m^3	9.38E+03	9.38E+03	9.38E+03
Metal depletion	kg Fe eq	2.89E+05	2.89E+05	2.89E+05
Fossil depletion	kg oil eq	2.89E+05	2.89E+05	2.89E+05

Table 4.
Life cycle impact assessment for each functional unit in the landfill biogas power plant.

5.2 Biogas from dairy manure

A well-known substrate for this activity is the waste of the livestock systems. Nowadays, there are several producers that use the manure of cattle for the generation of biogas [42–44].

The main objective of the LCA was to characterize the potential impacts of an electric power plant through biogas from dairy manure.

The study case scenario was a small-industrial generating plant with a generation capacity of ~ 22 kW, located in the dairy barn named "Establo Los Arados". The power plant is located in Meoqui, Chihuahua, Mexico (coordinates: 28° 14′35 "N 105 ° 28'14" W). The main activity is the dairy production; however, a biogas power plant was installed for both reduce operating cost in electricity consumption and managing the cattle manure generated.

In order to obtain the impact associated in 1 hour in the power plant, a functional unit of 22 kW h of electricity generation was selected. It is equivalent of the average power generated by the turbine installed. The boundary limits range from the manure collection to the power energy generation. These boundaries were defined based on the information access and the control parameters monitored in the power plant.

The harvesting system was divided into five main subsystems:

- Manure collection
- Barn infrastructure
- Biogas generation
- Power energy generation
- Power plant infrastructure

The pretreatment systems of both the substrate and biogas are included in the stage of biogas generation. Furthermore, a plant life of 30 years was assumed, considering a minor maintenance.

The unit processes and the boundary limits are illustrated in **Figure 3**. The water used in this process (blue line in **Figure 3**) is supplied by the barn. The green line (**Figure 3**) indicates the internal power supply. There are two different electricity sources considered: the municipal power supply and the biogas power energy generated.

The process of using biogas begins with the collection of manure. Because the power plant and the barn are in the same location, it is not necessary to travel long distances to transport the manure. The transport considers the route taken by the manure collector tractor, as well as the transport to the biogas production area. The continuous black line indicates the path of the substrate (manure). The substrate is transformed into the so-called stage of biogas production. This stage is separated into three substages: (i) pretreatment, (ii) anaerobic digestion, and (iii) purification. In this stage, waste is generated, such as solids (biosol) and effluent (biol). The biogas produced is taken to the stage of generation of electrical energy, which is incorporated into the supply line and for the self-consumption of the stable. In the stage of production of biogas, combustion gases are emitted, which were considered in the development of the inventories.

The operating conditions in the stages of the power generation, the water consumption and the energy consumption are information provided by the producers.

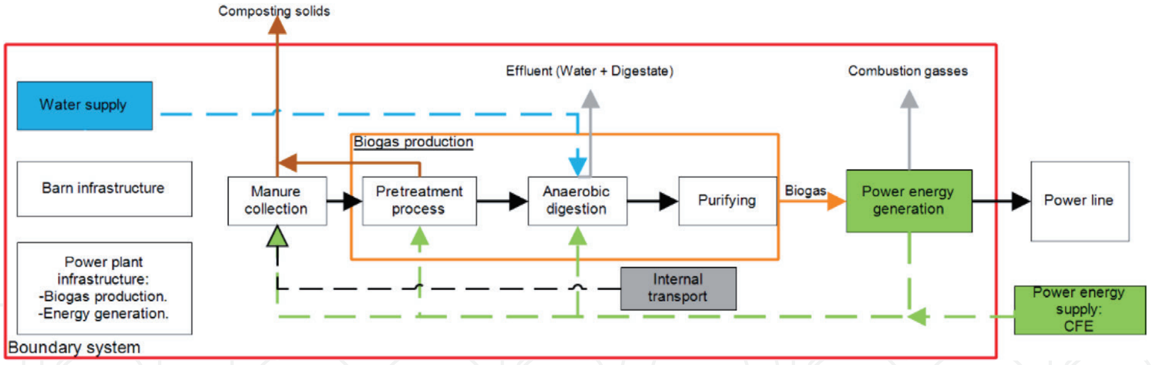

Figure 3.
Boundary limits for the dairy manure biogas power plant.

Literature information was included, mainly from the Ecoinvent database [41] and the parameters of the EPA-AP42 [45]. The literature information complemented the in situ measurements, which were carried out for both combustion gases (power energy generation) and effluent elements emitted (**Figure 3**).

The impact categories with a midpoint approach allow to assess the contribution of each of the systems with precision. **Figure 4** shows the percentage of contribution of each subsystem in the impact categories. This subsystem comparison allows to identify weak points and supports the technical decision making. Likewise, it allows to identify the direct impacts of production and the indirect impacts obtained from the consumption of resources.

Figure 4 shows a high contribution of infrastructure. It was identified that the electric power generation plant has an important effect in the categories related to depletion of resources, such as agricultural land occupation, ionizing radiation, urban land occupation, natural soil transformation, water depletion, metal depletion, and fossil depletion. It was found that the barn infrastructure contribute more than 80% of the total score in the categories of fossil depletion, freshwater ecotoxicity, and ozone

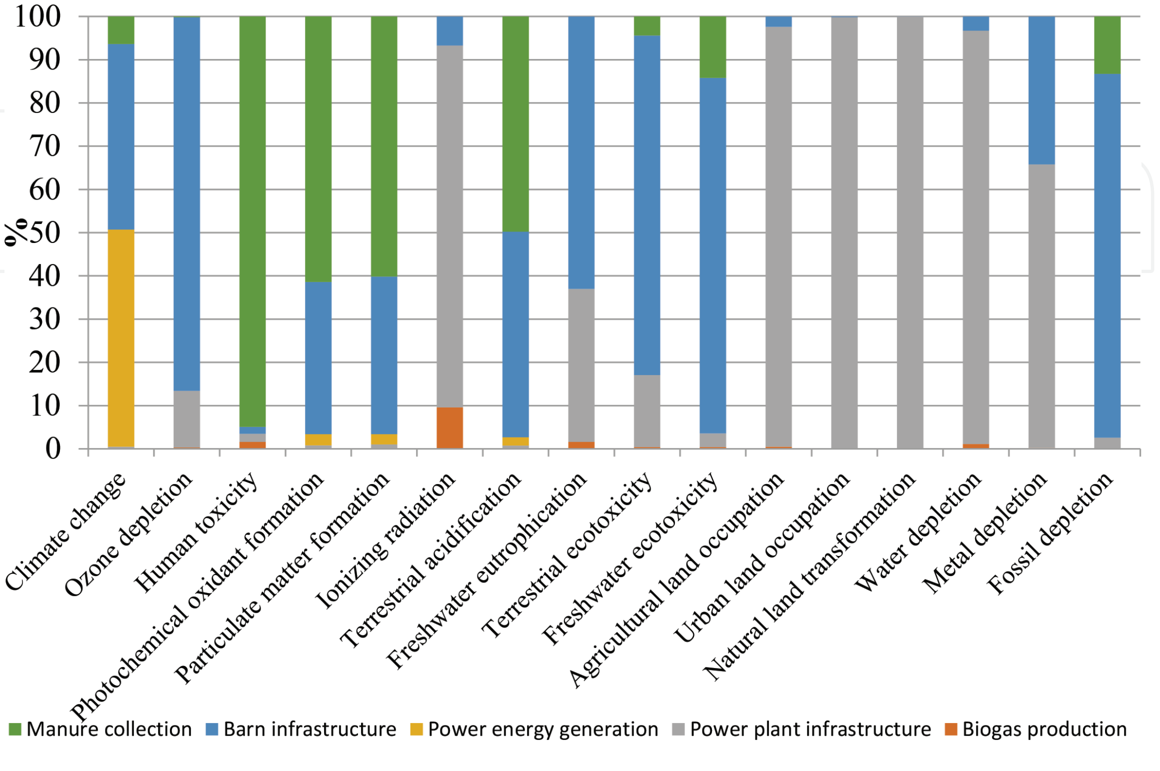

Figure 4.
Contribution for each impact category for biogas dairy manure power plant.

depletion. Likewise, it was considered maintenance of the barn was not relevant for the study. It was found that these categories show opportunity skills for decision-making.

The importance of the manure collection stage in the environmental load was identified. The usage of a machinery for transport and collection of excreta is difficult to modify due to the infrastructure adapted to the daily activities. However, it is possible to optimize the routes in the manure collection stage to mitigate the fuel consumption. With the appliance of this improvement, the environmental impact could be considerably reduced in the categories of human toxicity, photochemical oxidant formation, particle matter formation, and terrestrial acidification.

It was found that the generation of electrical energy is the main contributor to the climate change category due to the biogas combustion. Furthermore, the score in the categories of photochemical oxidant formation, particle matter formation, and terrestrial acidification is related to the generation of energy. However, this contributes to <10% of the total. So the power generation is the main opportunity skill in the category of climate change.

The identification of opportunity skills in the life cycle impact assessment allows stakeholders to make decision from a sustainable approach. On the other hand, in the life cycle assessment of the biogas landfill power generation, Section 5.1, sensitivity was analyzed by the comparison of different values in the functional unit to identify the most critical impact categories through the LCA.

6. Conclusions

Energy generation through biogas has gained relevance in recent years due to its potential capacity as a renewable energy source. An analysis of these technologies from the life cycle thinking is essential for sustainable development.

It was found that the separation of complex systems into subsystems or unit operations facilitates the development of inventories and the life cycle impact assessment. The infrastructure of the power plant initially implies an important contribution of potential impacts. However, with better practices and maintenance, better efficiency and useful life period, it mitigates the environmental impact.

The main impact categories (in the study cases) are related to the air emissions and water emissions. However, considering an efficient usage of the by-products, these emissions could be reduced. In the case of the power energy from biogas can be optimized if the by-products of the generation of biogas, like the digestate and solid phase inputs, are processed and conditioned to their usage as soil improvers. It reduces the environmental impact associated with the use of agrochemicals.

The LCA is a very useful tool for decision-making and environmental engineering. By using the general framework, any improvement in biogas power energy production could be incorporated in the system. In the study cases discussed in this chapter, the opportunity skills were detected, specifically, the combustion heat usage and the by-products coprocessing to mitigate the emissions. For future studies, more measurement data could be included.

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Conflict of interest

None declared.

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