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Assessment of Collective Production of Biomethane from Livestock Waste for Urban Transportation Mobility in Brazil and the United States

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Received: 25 January 2018; Accepted: 18 April 2018; Published: 20 April 2018

Abstract: Water, energy, and food are essential elements for human life, but face constant pressure resulting from economic development, climate change, and other global processes. Predictions of rapid economic growth, increasing population, and urbanization in the coming decades point to rapidly increasing demand for all three. In this context, improved management of the interactions among water, energy, and food requires an integrated "nexus" approach. This paper focuses on a specific nexus case: biogas generated from organic waste, a renewable source of energy created in livestock production, which can have water-quality impacts if waste enters water bodies. An innovative model is presented to make biogas and biomethane systems feasible, termed "biogas condominiums" (based on collective action given that small- and medium-scale farms on their own cannot afford the necessary investments). Based on the "farm to fuel" concept, animal waste and manure are converted into electrical and thermal energy, biofuel for transportation, and high-quality biofertilizer. This nexus approach provides multiple economic, environmental, and social benefits in both rural and urban areas, including reduction of ground and surface water pollution, decrease of fossil fuels dependence, and mitigation of greenhouse gases emissions, among others. The research finds that biogas condominiums create benefits for the whole biogas supply chain, which includes farmers, agroindustry, input providers, and local communities. The study estimated that biomethane potential in Brazil could substitute the country's entire diesel and gasoline imports as well as 44% of the total diesel demand. In the United States, biomethane potential can meet 16% of diesel demand and significantly diversify the energy matrix.

Keywords: water–energy–food nexus; urban mobility; biomethane; greenhouse gas emissions; renewable energy

1. Introduction

Recent significant global population increases and future predictions raise sustainability challenges for water, energy, food, and other sectors. The current world population of 7.3 billion is projected to reach 8.5 billion by 2030, 9.7 billion in 2050 and 11.2 billion in 2100 [1]. In this context, an extremely high-priority concern is to address interlinked water, energy, and food (WEF) systems.

The WEF "nexus" refers to the dynamics and trade-offs among interlinked resources—pillars that support the existence and survival of human life. This resource-security challenge is summed up as, "an urgent issue everywhere, and strong drivers of development and land use change, exacerbated by climate change, require new knowledge to achieve integrated solution using a nexus-based approach to assess inter-dependencies" [2].

At the global level, United Nations Water [3] advises that food production will increase about 60% by 2050, requiring 45% more energy and 30% more water. This means that increasing food production is virtually impossible without extra energy inputs, as energy is consumed in agricultural and livestock production for land preparation, manufacturing fertilizer and other agro-inputs, and transport (the latter is especially important in an era of long-distance trade of food and agricultural commodities). This scenario points to the need for sound planning of energy production and the use of renewable sources of energy, especially through greater efficiency of energy systems that consume minimal amounts of water.

At the present juncture, biogas stands as systemic source of energy generated by the planned treatment of waste from animal, vegetable, human and industrial sources—and the avoidance of environmental impacts through creation of economic assets directly (through the generation of energy for electricity, thermic and vehicular use from biomethane as well as bio-fertilizer) and indirectly (through the reduction of greenhouse gas emissions, thereby contributing to the mitigation of climate change). Unlike solar and wind sources, which are plagued by intermittent generation and contribution to the electrical grid, biogas can be stored and its energy distributed continuously.

Among the countries with the greatest potential for the use of biogas and biomethane (purified biogas), Brazil and the United States have very similar scenarios: they are among the countries with the largest populations and territorial extent (5th and 3rd in the world, respectively) [4], are leaders in food production (4th and 3rd) [5], are large energy consumers (9th and 2nd) [6], and are among the countries with greatest availability of freshwater water (1st and 3rd) [7].

This study assesses the collective production of biomethane from livestock waste for urban mobility in Brazil and the United States, taking into account biogas and biomethane potential and future perspectives. A Brazilian case study of an agroenergy "condominium" (so called for its multi-service approach to energy generation from biogas and biomethane, biofertilizer, and mitigation of GHG emissions) is presented with brief assessment on it replicability in other regions. Using Impact Matrix Cross-Reference Multiplication Applied to Classification (MICMAC) software and SWOT analysis methods, the study identified that farmers' key motivations to join the project were environmental and economic appeal, which demonstrated their environmental commitment. Less influential was social motivation.

This paper concludes with assessment of the implementation of collective production of biomethane with cost and technological implications for urban transport mobility, considering the resource scenarios and public policies in both Brazil and the U.S. Despite implementation and upscaling challenges, the results suggest that such arrangements bring considerable community benefits, enhance regional energy security, and contribute to a cleaner energy matrix.

2. Motivation and Problem Formulation

Livestock production has undergone major changes in the last decades [8,9], going from an extensive breeding and raising system to an intensive model of confinement. As a result of intensified waste concentration, environmental problems have also proliferated, requiring management alternatives that minimize impacts while recovering and valuing this waste.

One system of focus is biogas production, which consists of the decomposition of organic matter by bacteria in an anaerobic digestion process. In the absence of oxygen, organic matter is broken down and biogas is produced, composed mainly of methane, which can be converted into electric, thermal and vehicular combustion energy (Methane is 21 times more damaging to the atmosphere than CO_2, having a major influence on climate change. In biogas systems, the methane is captured, avoiding its direct emission; after combustion, CO_2 is released). The digested material (solids and liquids) can be used as fertilizer to increase agricultural productivity [9]. Besides producing energy from waste of the food production chain, the system enhances the sanitation of rural properties, minimizing contamination of water resources and the natural decomposition of waste that results in greenhouse gases generation. This process clearly integrates water, energy, and food elements and contributes to the generation of a renewable source of energy.

Considering that Brazil and the U.S. have meaningful potential for livestock production and, consequently, environmental challenges, the initial motivation of this research was to analyze the biogas potential in both countries and identify alternatives for improved use of this energy source. Because both rural and urban areas face sustainability challenges, analyzing their inter-relationship through the production of biomethane for use in urban transportation mobility represents a relevant challenge. The possibility of using biogas for urban mobility helps to address rural and urban challenges simultaneously, because the controlled digestion of rural waste prevents the emission of methane as a GHG and provides a cleaner, more reusable and efficient energy source.

Through collective forms of biomethane production from livestock waste, it is expected that increased numbers of farmers can participate in WEF nexus forms of production, reducing implementation costs, reducing environmental impacts of livestock production, promoting regional social and economic benefits, contributing to climate change mitigation, and energy matrix diversification.

3. Methods and Materials

Estimates of biogas potential in Brazil were based on the two-year study conducted by one of the authors titled "Opportunities of the Biogas Production Chain for the State of Paraná" [10]. With the data of biogas potential, it was possible to identify and calculate biomethane potential and its conversion to other fuels. Biogas potential for the U.S. was estimated using data from national agencies including USEPA, USDA, and the American Biogas Council. A database was created on potentials and conversion to other fuels. Other secondary data were collected from Itaipu Binational, CIBiogas and CIH's databases and technical reports, as well as published scientific articles.

The Ajuricaba project was selected as an illustrative case study; this serves as a reference project in the agroenergy sector and has important WEF nexus implications. There are other collective biogas projects implemented worldwide, but none has the scope and scale of the Ajuricaba, with dozens of small and medium farms.

Although there is considerable literature related to biogas and biomethane technologies, no other case study describes the agroenergy condominium model or presents and analyzes scientific and methodological data on real-world implementation.

Qualitative and quantitative analyses were based on primary and secondary data sources. Data were collected from Itaipu Binational, CIBiogas and CIH's databases and thereafter primary data were collected through interviews, data collection, and on-site visits, as summarized in Figure 1.

The interviews were conducted with 16 farmers who participated in the project and 7 professionals (engineers, technicians and managers) who contributed to the implementation of the Ajuricaba biogas condominium. Only the responses of farmers interviewed were considered for the conclusions, following a deductive approach [11]. The interview protocol was approved by the Brazilian National Ethics Committee, statement number 2.013.964.

Of a total sample of 33 property owners, 16 were interviewed, resulting in a confidence level of 95%, and a maximum allowed error of 7% [11]. After the interviews, all collected data were transcribed and tabulated. Content Analysis was used as a qualitative data analysis technique to identify what was said about a given topic and to decode what was communicated [12].

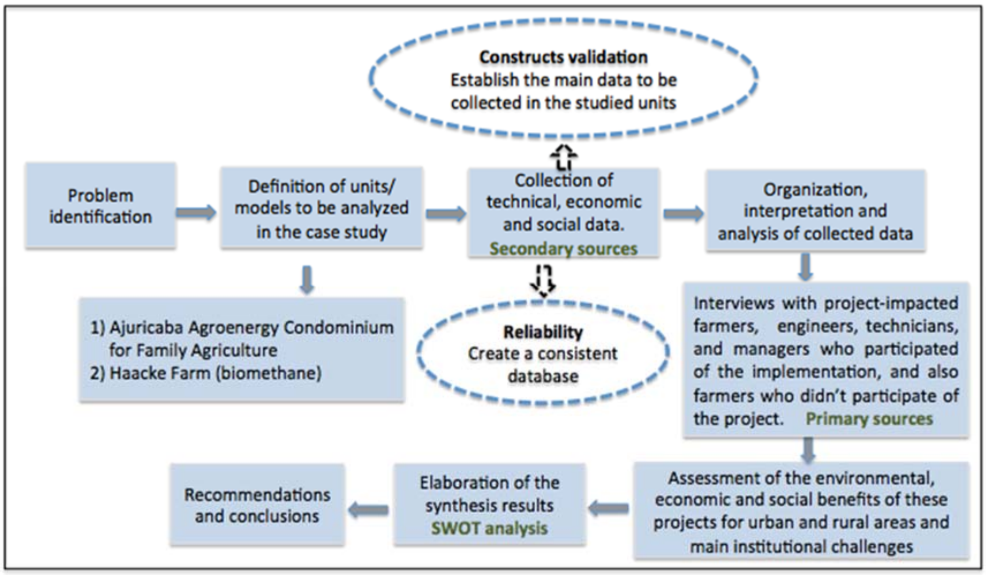

Figure 1. Outline of the case study research.

With the information consistently compiled, it was possible to analyze the most significant variables that determined farmers' participation in the biogas condominium. MICMAC (Impact Matrix Cross-Reference Multiplication Applied to a Classification) software was selected to eliminate possible calculation errors and give more support and credibility to the analysis [13].

The SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis method was employed [14] to assess the opinions of professionals (engineers, technicians, and managers) about agroenergy condominium implementation. Taken together, the results represent meaningful information for the replicability of this type of project in other areas as well as recommendations to support decision-making.

For context on livestock production in Brazil and the U.S. and forecasts to 2026, both grey literature (comprising chiefly government official reports) and published scientific literature were reviewed. This also included a review of Federal and State policies. Farm sizes were analyzed in both countries to evaluate the scale at which agroenergy condominiums would be viable and attractive for the farmers. To compare biomethane with other fuel sources, secondary information was collected from Itaipu Binacional and CIBiogas databases, based on the Haacke Farm pilot project. It was possible to calculate potential reductions of CO_2 emissions that would result from the use of biomethane compared to other transportation fuels and energy sources such as diesel, compressed natural gas (CNG), electric and hybrid-electric.

4. Water–Energy–Food Trade-Offs and Synergies of Biomethane

For the present Special Issue of *Energies*, it is especially important to establish the nexus dimensions of biomethane. Assuring water, energy and food security in a sustainable and equitable manner is a central challenge faced by planners, decision-makers, and resource users globally. UN Water [15] notes that, based on global demand trends, food production will increase 60% by 2050, requiring 45% more energy and 30% more water.

Interactions among water, energy and food systems are manifold. Water is required to produce food and energy. Energy is necessary to process and distribute water, and both energy and water are fundamental to any food enterprise. Food choices and agricultural practices influence water and energy demand, and, similarly, water, energy, and land demand for food production is influenced by different policies, such as those related to agriculture, energy, land-use, food, fiscal, credit, prices, and subsidies. These relationships and synergies are very dynamic.

These connections strengthen as the demand for resources increases with population growth and the move towards more resource-intensive lifestyles. These dynamics are combined with major trends such as climate and land use change, and the depletion of natural resources, which already limit the capacity of existing systems to meet increasing demands.

An integrated management of these three elements is required to face, as well as to curb, the current scenario with severe pressure on food, water and energy security and sustainable development in many places of the world. Figure 2 summarizes the interactions among water, energy (especially biomethane) and food.

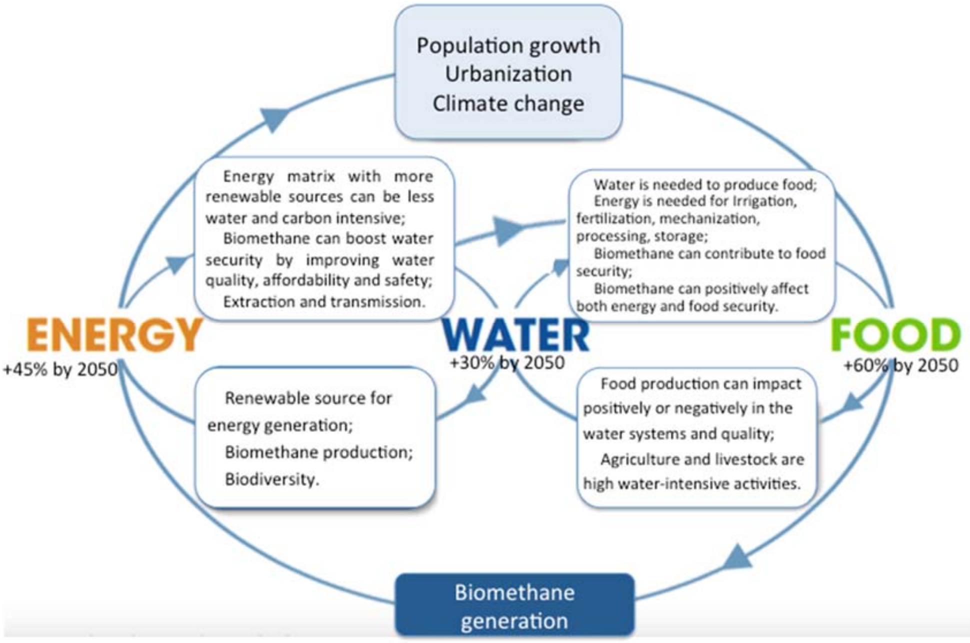

Figure 2. Water–energy–food nexus.

Biomethane production clearly integrates water, energy, and food, as it is the result of proper treatment of waste generated in food production, which consequently mitigates water pollution and reduces GHG emissions. With the use of biomethane, the energy matrix becomes more sustainable and diversified, reducing dependence on fossil fuels, while promoting local producers' development. In Brazil, the prices of diesel and gasoline increased 35% from 2011 to 2017. In the U.S., this increase was 6% in the last year [16].

Although food and water security are global challenges, their solutions are inherently local solutions, requiring coordination among rural and urban areas. As a result, this study demonstrated improved integration between rural and urban areas through the "farm to fuel" concept of waste produced on the farms being converted into biomethane for multiple uses such as urban for mobility.

4.1. Biomethane Potential for Brazil and the U.S.

Brazil and the U.S. are among the top countries in livestock production and have significant potential for biogas and biomethane production, as summarized in Table 1.

The U.S. has biogas production 2.6 times higher than Brazil's, representing an opportunity to reduce fossil fuel dependence and enhance energy security for farmers and local communities. Additionally, U.S. farms are more mechanized and consequently rural energy use is higher than in Brazil.

Table 1. Livestock biogas and biomethane potential for transportation in Brazil and the US.

Description	Brazil	US
Biogas production (million m^3/year) [1,2]	11,421.3	29,866.0
Biomethane potential (million gallons/year) [3]	1,961,171.9	5,128,344.6
Diesel potential (million gallons/year)	1667.42	4360.21
Gasoline potential (million gallons/year)	1848.34	4883.29
Passenger-miles driven per year with biomethane [17]	3,516,740	9,197,189
Total passenger-miles driven by passenger vehicle [17]	40,252,882,353	105,271,742,642
Number of buses powered per year [4] [18]	147,363	385,347
Number of people transported per year [5]	63,033,521,206	164,829,130,933
CO_2 emissions reduction per year (kg of CO_2 eq) [19] [6]	28,423,983	74,327,145

Source: adapted from Pasqual et al., 2017 [20]. [1] Only dairy cows were considered due to the total or partial confinement of these animals (that facilitates the logistics of manure collection), which is different from beef cattle, for example, that are essentially raised extensively on open pasture. [2] The manure production per animal per day was calculated considering 0.15 kg for broilers, 2.35 kg for swine and 12.5 kg for dairy cows [21]. [3] To calculate the biomethane energy potential, an average conversion factor of 0.65 was considered for equivalence to gasoline (or diesel, but not both together). [4] Bus diesel consumption of 31 gallons per day and fuel requirement of 0.5 gallons per km were considered [18]. [5] 1171 passengers transported per day per bus and 427,741 passengers per bus per year were considered [18]. [6] CO_2 emissions were generated using an emissions calculator [18].

Brazil's livestock biomethane potential of 1,961,171.9 million gallons per year represents the replacement or complement of 1667.42 million gallons of diesel or 1848.34 million gallons of gasoline, which is the equivalent of powering 147,363 buses per year and transporting 63,033,521,206 passengers annually. Considering that biomethane emits 85% less CO_2 than diesel when used to power a bus, the use of this renewable energy source for urban mobility would avoid the emission of 28,423,983 kg CO_2e per year. (CO_2e is a measure used to compare the emissions from various greenhouse gases based upon their global warming potential. For example, the global warming potential for methane over 100 years is 21, i.e., the emissions of one million metric tons of methane is equivalent to emissions of 21 million metric tons of carbon dioxide [22]).

The Brazilian Energy Research Company [23] argues that in addition to livestock, other sectors in Brazil could produce around 100 million m^3 of biomethane per day, which is equivalent to the total amount of diesel and gasoline imported in the country. Moreover, this is equivalent to 44% of the total supply of diesel demand.

U.S. livestock biomethane potential is 5,128,334.6 million gallons per year, which is equivalent to 4360.41 million gallons of diesel or 4883.29 million gallons of gasoline, sufficient to power 385,347 buses and transport 164,829,130,933 passengers annually. The use of this renewable source of energy for urban transportation would avoid the emission of 74,327,145 kg CO_2 per year. As the country has one of the highest energy consumptions in the world, the diversification of the energy matrix is especially relevant. Biomethane from livestock could replace or complement 16% of diesel demand in the country [24].

4.2. Collective Production of Biomethane Perspectives and Applications for Brazil and the U.S.

In the United States, the last Census of Agriculture was conducted in 2012 with the statistics reporting that 58% of total rural proprieties possess from 10 to 179 acres, representing 1,223,596 small- and medium-scale farms [25].

As the demand for livestock production will continue increasing in both countries, the raw-material for biogas and biomethane (organic matter) is assured in the coming years. In the U.S., the demand for meats and dairy products in both domestic and international markets is expected to remain strong and increase over the 2026 projection period for this analysis. Beef production is expected to rise at 1% per year, increasing from 25 billion pounds in 2016 to almost 28 billion by 2026. By 2026, pork is expected to slightly edge out beef production with 28.5 billion pounds of production. Poultry production is expected to continue increasing by about 1% per year [26].

In Brazil, broiler production is expected to grow by 2.8% annually by 2026. Pork production has projected growth of 2.5% per year and beef production is expected to grow by 2.1% per year [27].

In this context, the proper treatment of livestock waste is essential, raising the need for implementation of biogas projects potentially based on the agroenergy condominium model. In Brazil and the U.S., there is an increasing movement to encourage the use of biogas and biomethane in the energy matrix.

In December 2016, RenovaBio Program was launched in Brazil to foment the advance of the biofuels sector in the country through 2030. The program aims to provide economic and financial, as well as environmental sustainability, establish market rules and invest in new biofuels (such as second-generation ethanol, hydrotreated vegetable oil (HVO) biodiesel, sugar cane diesel, biogas, biomethane and bio-kerosene). It also aims at ensuring predictability for competitive participation of various biofuels in the Brazilian energy matrix, with emphasis on security of supply and recognizing the ability of biofuels to promote the decarbonization of the fuel market [28]. From the UNFCCC Conference of the Parties 21 (COP-21), the goal was established to reduce GHG emissions to 37% below 2005 levels by 2025 and 43% below 2005 levels by 2030. Biogas plays an essential role.

Public consultation on RenovaBio was opened in early 2017. The main points suggested for biogas and biomethane production incentives were: (a) to define the fuel-pricing factor based on already consolidated methodologies with the carbon intensity of the individual life cycle; (b) to stimulate the production of biogas and the shared generation of energies for groups of small producers via environmental licensing of their activities; and (c) to create a specific regulatory environment for flexible plants that allow valuation of the energy sources in their various end uses [28].

Regarding biomethane regulation, resolution No. 8/2015, from the National Agency of Petroleum, Natural Gas and Biofuels (ANP) [29], stated that biomethane produced from livestock products and waste (such as swine and poultry), agricultural and agroindustrial waste will be treated in the same way as natural gas. This means that biomethane may have the same uses as natural gas and have the same economic value, provided it meets the quality requirements of natural gas.

In the U.S., there are several federal and state regulations. At the federal level, the Environmental Protection Agency (USEPA) has recognized the benefits of supporting low-carbon fuels resulting from biogas, and in recent rulemaking, it classified many sources of biogas as cellulosic feedstock for transportation fuels as part of the renewable fuel standard, established by the Energy Policy Act of 2005 and expanded by the Energy Independence and Security Act of 2007 [30]. In 2016, the USEPA confirmed biomethane as an advanced biofuel, that is, it is considered to be renewable, low carbon, and capable of making a significant contribution to reducing greenhouse gas emissions.

At the state level, California has the most specific regulations for biomethane, as it is the nation's most populous state and has the highest biogas and biomethane potential. The reduction of methane emissions from livestock manure is a major component of the California Air Resources Board's (ARB) Short-Lived Climate Pollutant (SLCP) Reduction Strategy, aiming at reducing methane emissions by 40% from 2013 levels by 2030. Manure management practices by California dairies currently account for 25% of the State's methane emissions. The state enacted Assembly Bill No. 1900 in 2012 to increase and facilitate pipeline biomethane use. It stated: "standards for biomethane that specify the concentrations of constituents of concern that are reasonably necessary to protect public health and ensure pipeline integrity and safety" [31]. For injection to natural gas pipelines, biogas should be upgraded to biomethane by removing most carbon dioxide, producing a gas consisting of more than 95% methane [32].

The "Renewable Energy Program: Overall Program Guidebook—Seventh Edition" [33], released in 2013, describes specific aspects of how the California Energy Commission's Renewable Energy Program is managed and outlines terms and definitions. The eighth edition of the "Renewable Energy Program," released in 2015, considers biomethane only from landfill gas or digester gas [34].

Similar to Brazil, one of the challenges is the high cost of quality control for gas. The costs associated with cleaning, upgrading and injecting biomethane into natural gas pipelines must be supported by the producers. In this scenario, the concept of collective biomethane generation is more appealing, as the total biomethane production is higher than for individual production while the costs are distributed, often making the arrangement feasible. Taking into account the interviews held with farmers and technical staff who participated in the agroenergy condominium implementation, it was possible to identify the main opportunities and challenges for the implementation of agroenergy condominiums in Brazil and the U.S.

Small- and medium-scale farms are usually not able to afford high investments for biogas systems, so a viable alternative to manage manure is to create a condominium system with collective production. According to the latest Census of Agriculture in Brazil in 2006 [35], about 38% of agricultural establishments are family farms, which predominantly use family labor for the mainstay agricultural and livestock activities. About 48% of farms are smaller than 24 acres and 38% are between 24 to 247 acres, representing about 1,971,600 small- and medium-scale farms in the country.

In the case-study region of western Parana state (Brazil), described below, most of the anaerobic reactors built for swine manure treatment in the past were the plug-flow system (Figure 3). Basically, in this system, an anaerobic horizontal lagoon is covered with a geomembrane made of PVC and animal manure is supplied continuously or after the daily cleaning period of the facilities.

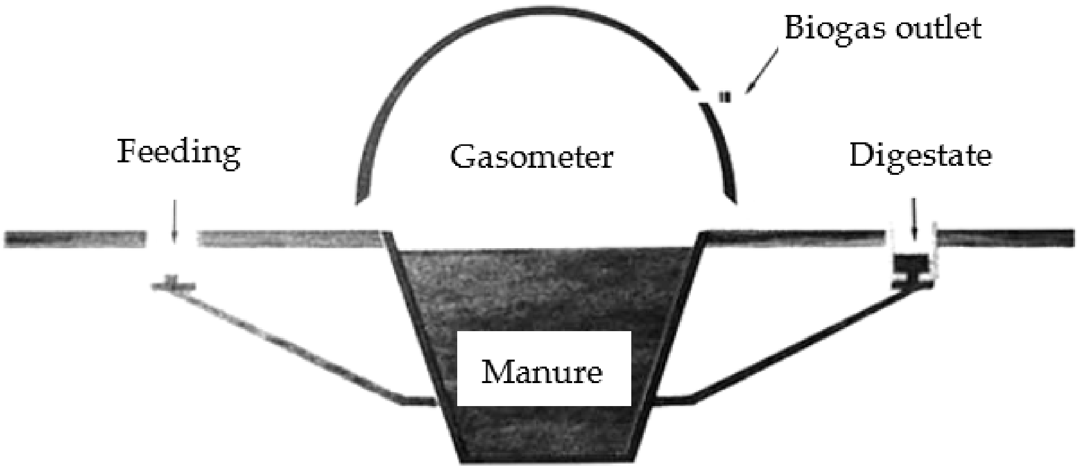

Figure 3. Basic structure of the plug-flow reactor. Source: Adapted from Embrapa [36].

These low-cost reactors are very well adapted to the local scenario, since the swine manure used as feedstock presents low solids content (usually under 10%) and high biodegradability—the relation between volatile solids (VS) and total solids (TS) is higher than 70% [37,38]. Furthermore, they do not require sophisticated equipment and, on the other hand, they have simple operation procedures that are easily incorporated into the regular rural activities, when compared to large-scale biogas plants. Major limitations of the plug-flow reactors installed in western Parana are related to the lack of temperature control, which leads to the high fluctuation of the amount of biogas produced and low efficiency during winter. Moreover, the lack of mixing facilities is often reported to be responsible for solids settlement, which reduces the working volume of the reactors and requires periodic sludge removal.

When other types of animal manure are considered, the plug-flow reactor does not necessarily fit the main physical characteristics, i.e., the amount of manure produced in the case of small farmers with dairy cow production (e.g., 30 animals average) or the very low moisture content of the chicken litter (TS usually above 30%) [39,40]. Thus, each animal manure requires a specific type of anaerobic reactor due to the physical and chemical characteristics each presents (Table 2).

Table 2. Methane potential by the type of animal manure.

Type of Manure	BMP * (mL CH_4 g VS^{-1})
Dairy	204 [41] 210 [42]
Chicken	259 [41] 283 [43]
Swine	323 [41] 293 [37]

* BMP: biochemical methane potential expressed in mL of methane per gram of volatile solids of manure.

To overcome the limitation of the anaerobic digestion of dairy cow manure in western Parana, an alternative low-cost reactor was designed and patented. In this concept, a small reactor made of fiberglass with working volume of 5 m^3 up to 50 m^3 has been used by small scale farmers with low manure production. As half of the chamber is placed under the ground level, it is possible to achieve acceptable temperature control and, at the same time, accumulate the biogas produced in the upper part of the chamber, located above the ground level (Figure 4). With this innovation, the biogas production of dairy cow manure became more feasible using the small amounts of manure produced on each farm.

Figure 4. Basic structure of the Biokohler anaerobic reactor. Source: Adapted from CIBiogas [44].

4.3. Ajuricaba Case Study: Agroenergy Condominium as a Technical and Social Innovation

Despite the significant availability of biogas in both countries, most small- and medium-sized farmers are unable to invest in energy generation projects. As a result, this research assesses collective production of biogas and biomethane, similar to such projects implemented in Paraná State, Brazil, by Itaipu Binational and the International Center of Biogas (CIBiogas). The Ajuricaba Agroenergy Condominium for Family Agriculture, the first functioning example of an agroenergy condominium in the world, fully addresses the livestock waste generated by 33 small properties, transforming it into an economic asset for the producers. The farms generate approximately 821 m^3 of biogas per day and 16,000 tons of waste/year, besides producing 14,000 m^3 of biofertilizer per year, which is an important contributor to agricultural productivity. The project also contributes to the reduction of 2.4 tons of CO_2 equivalent per year [44].

Currently, biogas in Ajuricaba is used as thermal energy for heating boilers at a local cooperative that processes poultry, in the farm's kitchen stove (replacing LPG, Liquefied Petroleum Gas), and also for heating water for cleaning dairy equipment. However, it can also be used as electric energy and can be purified and transformed into biomethane for use as vehicular energy [44]. Due to the lack of public policies and community calls for new energy acquisition since the project implementation, the conversion to electric energy did not work as expected. In 2017, the second phase of the project ushered in a new arrangement with the creation of the Association of Ajuricaba Biogas Producers, aiming at better organize the producers' activities and collective action.

To verify the major driving forces for farmers to participate in this kind of arrangement, individual interviews were held with 16 farmers. The questions considered environmental, economic, social, and institutional aspects, with results as follows.

Environmental: Eight farmers (50%) answered that they joined the project to solve environmental problems (chiefly through waste management); 87% considered that environmental problems were effectively addressed through the projects' mitigation of water and air pollution, pathogenic vectors on their farms, and reduction of GHG emissions.

Economic: Seven farmers (43.8%) participated in the project because they did not have to invest and wanted to generate new income. Overall, 93.8% of the farmers use the biofertilizer produced in their farms, increasing land productivity and moving the crop they harvest forward from 90 to 30 days, and promoting an annual average saving of USD 600 in fertilizer. Fifty percent use biogas stoves, saving about USD 200 of LPG per year. Farmers indicated that greater government incentives would permit more producers and rural properties to participate in this type of arrangement. They also suggested a financial participation, at least symbolic, of each farmer in the future, as currently no financial match is required, resulting some farmers not taking it seriously (in this pilot project, Itaipu invested approximately USD 1.3 million from its Research & Development fund).

Social: One farmer (6.25%) informed that his participation was to ensure better quality of life for the next generation; farmers argue that the project strengthened family farming, attracting their children to stay on the farm. The condominium also promoted cooperative work between neighbors as evidenced by women's role in sensitizing their husbands and insisting on participation in the project. Due to significant reductions of pathogenic vectors and bad odor, the properties use less chemical control, thus improving the producers' quality of life.

Institutional: Fifteen farmers (93.8%) affirmed that the technical support offered by the project was fundamental for their participation in the condominium as they trusted the work and the recommendations of the technicians from Itaipu and CIBiogás, who were available on demand. Overall, 50% had their expectations met during the design, implementation and maintenance phases of the project and the other half recommend more profit for farmers in future projects; 88% recommended the agroenergy condominium to other neighbors; and 12% affirmed that would recommend it only if it were more profitable. The production of biogas and biofertilizer depends on technical assistance, both to monitor the farms' performance and to encourage producers to maintain their commitments. Another important issue identified was the need to recognize the vocation (both technical and social) of the producers who will participate in the project, since some do not have the dedication or real will to produce results.

Based on the answers given to the questions, the ten ideas most frequently mentioned by the respondents were identified as key variables:

1. Environmental motivation to participate in the project (Env. Mot.)
2. Social motivation to participate (Social Mot.)
3. Economic motivation to participate (Econ. Mot.)
4. Willingness to participate in the second phase of the project and commercialize biogas (2nd Phase)
5. Possibility to solve environmental problems (Sol. E.P.)
6. Possibility to use biogas to cook (Stove)
7. Possibility to produce a biofertilizer (Biof.)
8. Possibility to have specialized technical support (Tech. Sup.)
9. Possibility to meet your expectations and needs (Expec.)
10. Recommendation to your neighbor to participate of the project (Recomm.).

From the MICMAC analysis, it is apparent that the main drivers of farmers' participation this agroenergy condominium were economic profit and solution of environmental problems, which represents farmers' "environmental citizenship" (their sense of obligation and motivation to preserve natural resources, care for ecosystems, and minimize environmental impacts due to pollution [45]), as presented in Figure 5.

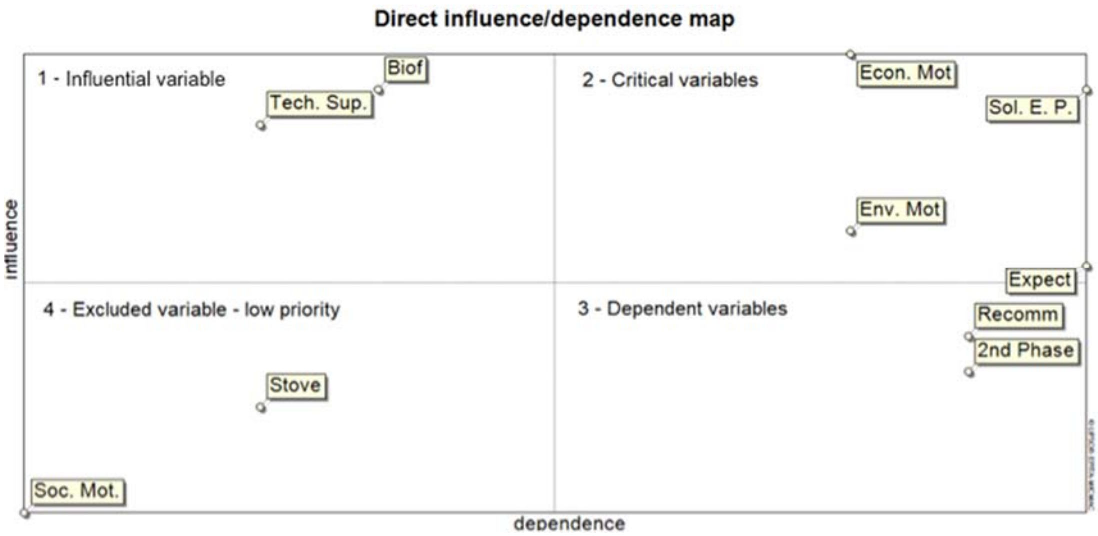

Figure 5. MICMAC direct influence-dependence plot.

The variables Technical Support and Biofertilizer, presented in Quadrant 1 (Q1) represent high influence and low dependence. This means that the producers are highly influenced to join and remain in the condominium by the technical support and the use of biofertilizer. The critical variables in Q2 are at the same time highly dependent and highly influential, presenting an instability, which means that any action on these variables will affect other variables, and vice versa. Frequently, these variables represent the most challenging aspects of project implementation.

The recommendation and implementation of the 2nd phase of the project, in Q3, are less influential and highly dependent, which means they are the results whose outcome is linked to the mainly influential variables in Q1 and Q2. The Biogas Stove and Social Motivation in Q4 represent less influential and less dependent variables. They constitute factors relatively disconnected from the system due to their independence. Social Motivation is the least influenced and least dependent variable.

These analyses indicate that for other agroenergy condominiums, it will be necessary from the project design stage to give special attention to environmental and economic factors. The least important motivation was social (cooperation with neighbors, sense of community, etc.). These elements are fundamental for the 2nd phase of the project, however, and are also very important for implementation and replication of other agroenergy condominiums.

In addition to the benefits provided by the biogas project, another possibility is the generation of biomethane for fueling local cars and, on an even larger scale, for fueling rural and urban buses. Because Ajuricaba's biogas production is all being used by the Cooperative and the farmers, the biomethane project must wait for increases in waste production. The results of the biomethane analysis and refining methodology as used on Haacke Farm, located close to Ajuricaba, are presented. This farm has 80,000 laying hens and 750 cattle, producing a total of 1000 m^3 of biogas per day, as a result of the manure generated and treated in the anaerobic system.

The biogas generated on the Haacke Farm is composed of 64% methane. Through the refining process, 98% of biogas is converted into biomethane with the characteristics of compressed natural gas (CNG), meeting regulations No. 16/2008 and No. 08 of the National Agency of Petroleum, Natural Gas and Biofuels (ANP), which establish the minimum target of 96.5% methane and at most 3% CO_2 and 0.5% O_2.

Tests conducted by the farm, in partnership with Itaipu Binational and Scania, concluded that biomethane has significant advantages compared to other energy sources. A Scania Euro 6 bus powered with biomethane carried 3250 passengers in the Itaipu complex, running 3000 km in 19 days of monitored tests. The average consumption was 1.90 km/m^3, similar to the consumption of CNG and 40% more efficient than diesel. It avoided the emission of 100 tons of CO_2 equivalent, representing a 70% reduction compared to a diesel-powered bus. Additionally, the biomethane cost was 56% lower than the diesel [44].

With the results obtained in the Ajuricaba Condominium and Haacke Farm pilot projects, it was concluded that the agroenergy condominium can bring environmental, economic and social benefits for the local community and the region, contribute to more sustainable rural development, and enhance regional energy security. For future condominiums, it is possible to significantly improve processes and biomethane and biofertilizer production while reducing the costs for implementation, maintenance and operation through the lessons learned in these pilot projects.

After analyzing farmers' perceptions, interviews were held with seven engineers, technicians and managers who participated in the project design and implementation. Through a SWOT analysis, it was possible to identify the main strengths, weaknesses, opportunities and threats related to the project. These are synthesized and presented in the next session.

All those interviewed considered that Ajuricaba was an important project for breaking rural energy paradigms by developing innovative processes and products not tested earlier, e.g., overcoming known limits of both the biodigestors and the biogas collection network, thus facilitating replication. As a first test case globally, some results were below expectation—some technologies did not work as expected and needed to be replaced or adapted.

For future implementation, it was suggested to invest in biomethane for urban mobility, mainly due to the positive results of the Haacke Farm project, which demonstrated that the economic benefits are of greatest interest to producers. Nevertheless, the volume of biogas production needs to be higher than local demand as seen in Ajuricaba.

5. Findings and Results Discussion

Based on this research, the main results achieved are described as opportunities for the implementation of other agroenergy collective production and main challenges that are necessary to overcome.

(1) Opportunities

(a) Environmental: With projections of livestock production increases in the coming years, the proper treatment of waste is essential, strengthening the need to use biogas and biomethane systems; promotion of synergies between the water–energy–food nexus; water and soil quality enhance though anaerobic digestion; environmental sanitation in the properties that compose the condominium and the region where it is located; reduction of pathogenic vectors; better spatial organization of the farms and cleanliness; reduction of GHG emissions with the biogas system and also with the optimized logistics proposed in agroenergy condominiums; stimulate the less dependence on fossil fuels and vulnerability to depend only in few sources of energy; and environmental awareness and better joint action of communities.

(b) Economic: This type of arrangement boosts the importance of family farming, that is very representative in Brazil and the U.S., augmenting their financial health and perspectives for new investments in the property; use of electric, thermic and vehicular energies for self consumption in the farms and sale of the surplus for local companies; use of biofertilizer for increasing agricultural production, increasing the project's viability, since is produced more with less investment; economy with the use of biogas stove, replacing the use of LPG; and development and creation of national technologies to replace imported ones, strengthening national companies. This issue is linked to the circular economy concept, which means that resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops; valuing waste, through biogas and biomethane generation processes, raises investments in this source of energy.

(c) Social: It strengthenx family farming production and attractiveness of farmers to stay in the field due to the project. The inclusion of biogas technologies creates changes in the routine and attracts discovery and technological innovation, favoring the inclusion of new generations (children) in the routine of family agriculture, including, encouraging entrepreneurship in the specialized biogas services sector; associative work; creation of a biogas association; adding importance to women's role to convince their husbands to participate actively in the project; better quality of life in their properties; reduction of bad smell and pathogenic vectors, such as flies and insects; and introduction of biogas management in the farmer's routine, increasing their awareness about the environment.

(d) Institutional: Alliance of expert companies that act in inter-related sectors of biogas production chain develop the most suitable management, based on their knowledge and expertise; biomethane management solutions to implement in future condominiums or projects; learning about managing different interests of people and companies; management challenges and solutions for being an innovative project; and the technologies implemented have known limits now, facilitating the replication of the condominium in other places and providing more credibility to the involved companies. Repetition of experiences even creates elements and validations for creating credit lines and financing family farming.

(e) Technological: During the implementation of the agroenergy condominium, many technologies and processes were improved and even created, such as the small-scale fiberglass biodigestor that was installed according to the specific situation and type of manure of the properties; the installation of an extensive low pressure biogas collection network (25.5 km) was a new technology in Brazil and worldwide; development of national technology to replace imported ones; and the technologies implemented have known limits now, facilitating the replication in other places and improving the products even more. Among these bottlenecks are the cost of volume measurement and biogas and biomethane compression technologies. Biogas and biomethane is the renewable source that most closely resembles hydraulic energy, as it can be stored and dispatched continuously and, unlike solar and wind sources, they provide uninterrupted input into the grid. In recent years, some regulations for biomethane were stablished in Brazil and the U.S., stimulating the use of this source of energy. The development of the project encourages the public discussion of the solution and creation of standards and parameters of quality and safety.

(2) Challenges

(a) Environmental: A very detailed study of the types and quantities of waste generated in each property at the design stage of the agroenergy condominium is necessary, so that the project is implemented under the right conditions and without significative estimate variations; need of efficient corrective and preventive maintenance of the biogas system to avoid environmental problems and impacts; and importance of daily monitoring procedures to evaluate the results and detect possible disruptions.

(b) Economic: The farmers who participated in the pilot project recommended a small financial involvement of farmers for future projects, so they can valorize the project and be more responsible for their results. As a Research and Development funded project, it was designed to develop new technologies, not to generate profit, but for future condominiums a profit forecast is necessary. The challenge is to find the relationship between investment and results; the main driver of biomethane penetration in the fuel market is the fuel cost, compared to fossil fuels, which requires incentives and public polices; cheap and abundant natural gas has made it difficult for biomethane and other renewable technologies to compete with fossil fuels; and the cost of equipment and their service life need to be seriously taking into account, as some of them did not work as expected and needed to be replaced, such as the compressors.

(c) Social: At the outreach and promotion phase of the project, it is recommended to deeply evaluate the farmer's vocation to participate in this kind of arrangement—some farmer's actions and commitment were below expectation in the pilot project and some of them did not understand their important role to obtain results for the collective. The communication with farmers need to be frequent and clear, so they can trust in the project. It is advisable to develop contracts or terms of commitment after the promotion phase. The key of this phase is that the expectations of the participants are adequately managed. Another important point is that there should be a timetable to be disseminated and respected, and if changes are needed, these should be widely disseminated among all farmers. Social gains (such as collaborative work and increasing knowledge) are not so valorized as economic gains, so this appeal must be reinforced. Farmers nee training and motivation to obtain better results and encourage them to work as a team. It was difficult for producers to act in an associative way.

(d) Institutional: Diffuse interests of the partners are a crucial point in the project, so the involved companies need to clearly establish their role and responsibilities and create a good synergy; it is essential that suppliers are as close as possible to the condominium, as it strengthens the local economy and gives a better application of regional development; efficient technical assistance is necessary, demanding organization and commitment from the involved staff; the high turnover of technicians and involved suppliers ends up weakening the farmer's reliability; the lack of specific regulations for rural biogas collection networks added difficulty to the project operation, as today it only exists for large scale; and the lack of state-level mechanisms, for example "feed-in tariff," which is a policy mechanism designed to accelerate investment in renewable energy technologies.

(e) Technological: During the project implementation, technological limitations were identified, such as difficulties to operate the micro thermoelectric central and low performance of the original moto-generator for electricity generation; some materials did not correspond to their purposes, needing to be replaced; importance of a detailed project design, as biogas production was overestimated at the beginning, not considering temperature variations and sanitary void. Regarding the anaerobic reactors, it is necessary to incorporate technological devices to keep temperature in the optimal mesophilic conditions (35 °C) during the entire year. A mixing strategy needs to be added to improve hydraulic flow and, thus, increase the methane production and reduce the necessity of periodic sludge removal. Moreover, frequent scientific investigations about new types of biomass, including agricultural waste, need to be developed to take advantage of the existing facilities and, thus, improve the biogas yield of the farm.

Use of Biomethane for Urban Mobility and Reduction of Fossil Fuel Dependence

Increasing population and urbanization require significant changes in urban mobility patterns; the use of renewable fuels will be essential in the coming years. The current patterns of urban mobility in Brazil and the U.S. contribute significantly to GHG emissions.

The transportation sector is a high-energy consumer in both Brazil and the Unites States, responsible for 32.2% and 28.0% of the total energy use, respectively. In both countries, fossil fuels are dominant in this sector: in the U.S. they account for 89% of total transportation energy—the highest consumption is of gasoline (59%) followed by diesel (25%), with biodiesel and ethanol representing 7%

and natural gas 5% [46]. In Brazil, fossil fuels represent 76% of total transportation energy, with the highest consumption being diesel (45%), followed by gasoline (29%), and ethanol (24%) [47].

To help cities address climate change challenges, emphasis must be placed on increased use of biomethane, which "GHG emissions [that] are virtually zero, because the CO_2 produced by recovering the biomethane has previously been captured by the decomposed organic matter". A European Union study [48] affirms that the GHG footprint of biogas and biomethane are the lowest of any renewable sources of energy for vehicular use.

Electric vehicles are often considered one of the cleanest vehicles for urban mobility, but it is important to consider that the production of electricity is based on sources of energy that are not always clean and renewable. A study in the U.S. on the impact of electric vehicle pollution concluded that in the northwest of the country, in states such as Washington and Oregon, electric vehicles are less polluting than, for example, in Illinois. This is not because the vehicles in each region are different, but in the northwest region the electric energy is generated through hydropower and nuclear power plants, while in the Illinois region the energy is generated mainly by coal-fired power plants [49].

Compared to the main fuels for urban mobility using buses (diesel, CNG, electric, and hybrid-electric), biomethane has several environmental and economic advantages. In relation to diesel, biomethane has similar energy yield, yet emits 85% less CO_2 to the atmosphere and minimizes other pollutant emissions associated with its production chain, given that it is produced from waste and manures that would otherwise be less well treated if there were no biogas and biomethane production system. Compared to CNG, biomethane for bus transport emits 80% less CO_2 [50]. In addition to these advantages, biomethane must be considered a complementary renewable fuel and the raw material (rural or urban waste) for the digestion process is ubiquitous—different from other renewable energy sources such as solar, wind and hydroelectric power.

In Brazil, Federal Law No. 12,587 of 2012 established the National Policy on Urban Mobility, containing principles, guidelines and fundamental instruments for changing traditional mobility patterns. Notable among these are: (a) prioritizing collective public transport projects that drives integrated urban development; (b) encouraging scientific and technological development and the use of renewable and less polluting energy; and (c) monitoring and control of local and greenhouse gas emissions from different modes of transportation [46].

In the U.S., the "Planning for Federal Sustainability in the Next Decade "Executive Order 13693 of 2015 introduced new requirements established by EO 13514 (Energy Policy Act of 2005), and the Energy Independence and Security Act, of 2007. EO 13693 aims at integrating the values of sustainability, stewardship, and resource conservation into all policies, programs, operations, investments, and research. Some priority goals include achieving greenhouse gas emissions reduction targets, reducing energy intensity in buildings and fuel consumption in vehicles, and increasing use of renewable energy and alternative fuels [30].

6. Conclusions

The predictions of intense urbanization and population growth over the coming years will heighten the need to ensure water, energy and food security, given that demand to 2050 is projected to increase by 30%, 45% and 60%, respectively. The purpose of studying the inter-related nexus of all three resources is to co-optimize resource use in the face of production increases, reduce pressure on water and land use, and achieve higher energy diversification and efficiency while minimizing negative environmental and social impacts.

This research demonstrates opportunities for the integration of energy, water, and food through the conversion of livestock waste into biogas and biomethane, with applications for urban mobility. This study sets the stage with the estimation of biomethane production in Brazil and the U.S. Both countries have meaningful potential and have similar conditions, as they are among the leaders in food production, are large energy consumers, and have the greatest availability of water.

Through the biomethane estimation for both countries, this study addresses technical approaches and their interrelated variables: environmental, economic and social aspects, interrelation between the benefits of biogas and biomethane for rural and urban areas, structural and institutional changes for the establishment of agroenergy condominiums, and energy security. To identify opportunities and limits of biomethane, the Ajuricaba case study was used to illustrate how small and medium farms generate biomethane. With the farmer's interviews, it was possible to conclude that the project achieved relevant environmental benefits to the local community and was considered satisfactory by the farmers.

With the MICMAC analysis, it was concluded that the main motivators for the participation of farmers in an agroenergy condominium are economic and as a solution for environmental problems. This indicates that, for other agroenergy condominiums, it necessary to give special attention to both factors, starting from the project design. It was also emphasized that, for the good performance of this arrangement, the management strategies must consider the appropriate profile and vocation of the participants, such as type of production in farm and the farmer's willingness in join and implement the project, aiming at prioritizing committed farmers and enhance the results. The results of this pilot project in Brazil demonstrate the potential of biogas production, the reduction of costs and risks for producers, and how this arrangement can bring significant environmental, social and economic benefits to farmers locally and regionally.

The article concludes that it is possible to integrate water, energy and food processes through biogas and biomethane systems by generating energy from livestock waste, avoiding water and air pollution and contributing to climate change. In addition, rural and urban areas can provide multiple benefits locally and to regional and national energy matrix diversification.

Acknowledgments: The authors gratefully acknowledge the International Center of Renewable Energies—Biogas and the International Center of Hydroinformatics for the data availability, the Pontifical Catholic University of Paraná and Coordination for the Improvement of Higher Education Personnel (CAPES) for funding. In addition, partial support for the participation of Christopher Scott was made possible by the Inter-American Institute for Global Change Research (IAI, project CRN3056, which is supported by the U.S. National Science Foundation Grant GEO-1128040), the Lloyd's Register Foundation (a charitable foundation helping to protect life and property by supporting engineering-related education, public engagement and the application of research), and the Morris K. Udall and Stewart L. Udall Foundation.

Author Contributions: Janaina Camile Pasqual, Harry Alberto Bollmann, and Thais Carlini Baptista conceived, designed, and performed the experiments; Janaina Camile Pasqual and Christopher A. Scott analyzed the data; Thiago Edwiges contributed to the analysis tools.

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

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