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Bioenergy transition as a strategic mechanism to diversify energy sources in rural areas in Colombia

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Abstract. The growth in population has resulted in an increase in the consumption of goods and services, which has led to a surge in waste generation and the use of fossil fuels. To mitigate the envi-ronmental issues associated with improper waste management and reduce greenhouse gas emissions from fossil fuels, residual organic matter can be used to produce bioenergy in the form of biogas and biomethane through anaerobic digestion (AD). These biofuels can act as substitutes for liquefied petroleum gas (LPG) and natural gas (NG) and can be utilized for power and heat generation. In Colombia, the current production of biogas is 4 MW, and the government aims to increase its utilization by promoting the inclusion of biogas and biomethane in the energy matrix through a supportive regulatory framework. Studies suggest that the theoretical energy potential of livestock waste in Colombia is estimated to be 2,673 MW, but the current technological conditions allow for the utilization of only 198 MW, with the pork sector contributing 34%. This study examines the legal context and the present state of biogas in the Colombian energy matrix, while exploring the potential of the Colombian pig farming sector for biogas production. The social, economic, and environmental barriers and opportunities faced by this sector in becoming an energy producer during the transition period are also identified. The findings suggest that biogas presents a sustainable energy solution for rural areas of Colombia where pig farming is a prominent economic activity. Biogas can replace traditional fuels like LPG and firewood for cooking purposes or serve as a complementary source for electricity and thermal energy production in non-interconnected zones. This could mitigate environmental issues and reduce the prevalence of respiratory diseases associated with the use of firewood.

Key words: bioenergy, livestock, fossil fuel, greenhouse gas, manure.

INTRODUCTION

The use and exploitation of fossil fuels as a primary source of energy and raw material have resulted in severe water, soil, and air pollution. The combined impact of population growth, increased energy demand, and the greenhouse gases (GHGs) emission, along with the desire to reduce dependence on fossil fuels by importing countries, has led to the emergence of initiatives and research on renewable energy resources and technologies. The integration of renewable energy into the energy mix has shown tremendous environmental benefits and provided an economic driving force that stimulates technology development while creating job opportunities. Nonetheless, the implementation of these technologies must adjust to the variability and dispersion of energy resources.

Several studies have shown that the most appropriate way to produce energy with renewable technologies is through decentralized and complementary generation that meets the energy needs of a specific area using available energy resources (Ahmadi et al., 2015; Khan et al., 2017).

Due to Colombia's topographical characteristics and agricultural vocation, decentralized energy production is a suitable model for the country's subregions. The complexities of Colombia's relief increase the costs of extending the electric grid and fuel coverage throughout the national territory, particularly in rural and remote areas. Thus, the different national energy plans developed in the last two decades have focused on decentralized energy production and increased participation of renewable energy in the energy mix (Unidad de Planeación Minero-Energética, 2020). However, bioenergy has not received the attention that other renewable energies such as solar and wind have garnered. The potential of bioenergy has primarily focused on the production of liquid biofuels for internal combustion vehicles and GHG emissions reduction (Centro de Información y Documentación Palmero, 2015; Delgado et al., 2015), while biogas has been treated as a by-product of wastewater treatment processes and organic matter decomposition in landfills.

Although some sectors have made efforts to incorporate biogas as an energy source in their production processes, the utilization of biogas in rural areas, where the largest amount of raw material for its production is available, is still low. These territories require improvement in the supply of thermal and electrical energy to the residential, commercial, and industrial sectors. Therefore, the production of biogas from livestock waste is an alternative that would allow meeting some of these needs, particularly in households for cooking and electricity, which would reduce costs for rural families and improve their quality of life. Moreover, the by-product from the transformation of organic waste, the digestate, can be used as a fertilizer, reducing production costs for small and medium-sized farmers.

This article aims to analyze the current Colombian energy matrix and potential scenarios for the year 2050 to showcase the relevance of bioenergy in the energy matrix, particularly biogas as a tool for the energy transition. It presents the legislative framework for biogas evolution and a comparative analysis of different energy sources to highlight the advantages of biogas utilization. Additionally, the article aims to establish mechanisms for incorporating biogas into the energy matrix of rural areas, considering the economic, environmental, and social barriers and opportunities present in these regions of Colombia. Furthermore, it demonstrates the livestock sector's potential for biogas production, with the pig sector currently having the highest technical potential compared to other livestock subsectors in Colombia. Finally, the article showcases biogas' ability to meet the demand for LPG and firewood for cooking in rural areas and its potential to meet part of the demand for electricity in non-interconnected areas of the country by utilizing organic waste.

MATERIALS AND METHODS

Data sources

The present study is primarily based on a comprehensive analysis of secondary sources of information. These sources include a wide range of publications from reputable national and regional government bodies, as well as energy and agricultural sector associations, and peer-reviewed scientific articles. The data and information required for this study were primarily accessed through the entities' web portals and scientific databases.

The available documents were carefully selected, taking into account their relevance and reliability, and included development plans, academic and scientific studies, reports, periodic bulletins, manuals, investigative journalism reports, laws, resolutions, and scientific articles. The diverse range of sources provided valuable insights into the subject matter and allowed for a thorough analysis of the different aspects related to the topic.

Table 1 presents a comprehensive list of the primary government entities and associations that were consulted during the research. The table also includes the corresponding references to the documents from which the information was extracted. By providing this detailed information, the study aims to ensure the transparency and reliability of the sources used, thus enhancing the credibility and validity of the study's findings.

Data analysis

The information gathered has been organized into three distinct thematic groups. The first group examines the Colombian energy matrix, including its current status, context, and future scenarios, with a particular focus on bioenergy. The second group contains information on the Colombian livestock sector and its connection to the use of residual biomass. Finally, the third group pertains to the energy situation in rural areas of the country.

Upon categorizing the information, an assessment of the current state of the national energy generation and consumption matrix is conducted. This assessment is achieved by determining the percentage contribution of each energy source. Potential energy scenarios for Colombia in 2050 are then identified, utilizing the guidelines provided by the national government for the development of the energy transition. Moreover, the desired objectives of increased renewable energy participation, energy matrix decarbonization, and GHG emission reduction are also taken into consideration.

Additionally, by utilizing information on the context of the livestock sector and biogas production in Colombia, the energy potential of the bovine, pig, and poultry subsectors is determined. Possible forms of biogas utilization in various sectors of the country are identified, considering their contribution to the energy scenarios projected for 2050 and the goals to be achieved in the development of the transition.

Finally, based on an analysis of the information gathered on the energy context of rural areas and the characteristics of biogas production from the previously analysed livestock sector, particularly from the pig sector, barriers and opportunities (social, environmental, and economic) of biogas utilization as a tool to meet energy needs in these regions and its contribution to the energy transition process are identified.

Table 1. Principal data and information sources

Organisation	Acronym	Type of organisation	Referencias
Ministerio de Minas y Energía	MinMinas	Governmental	Ministerio de Minas y Energía, 2017; Velásquez & Rincón, 2018; Ministerio de Minas y Energía, 2021
Ministerio de Medio Ambiente y desarrollo sostenible	MinAmbiente	Governmental	Roa et al., 2020)
Unidad de planeación minero-energética	UPME	Governmental	Ministerio de Minas y Energía, 2011; Ministerio de Minas y Energía, 2015; Ministerio de Minas y Energía, 2017; Velásquez & Rincón, 2018; Ministerio de Minas y Energía, 2021
Comisión de regulación de energía y gas	CREG	Governmental	Ministerio de Minas y Energía, 2016
El Instituto de Planificación y Promoción de Soluciones Energéticas para las Zonas No Interconectadas	IPSE	Governmental	Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas – IPSE, 2023a
Departamento administrativo Nacional de Estadística	DANE	Governmental	Departamento Administrativo Nacional De Estadística - Dane, 2018
Instituto Colombiano Agropecuario	ICA	Governmental	Instituto Colombiano Agropecuario ICA, 2023
Asociación Colombiana de Gas licuado de Petróleo	GASNOVA	Private association	Asociación Colombiana del GLP - GASNOVA, 2023
Asociación Colombiana de Porcicultores	Pork Colombia	Private association	(Asociación Colombiana de Porcicultores, 2021; Fajardo López & Zambrano, 2021; PorkColombia, 2021)
Federación Nacional de Biocombustibles	Fedebiocomb ustibles	Private association	Centro de Información y Documentación Palmero, 2015; Federación Nacional de Biocombustibles, 2019

POLICY BACKGORUND

Strategic National Energetic Plan (2022–2050)

The Colombian energy sector heavily relies on hydroelectricity (70%), followed by fossil fuels (29%) and non-conventional sources (1%). This overreliance on water resources is problematic, as it makes the energy sector vulnerable to climate change and the limited availability of fossil fuels. Furthermore, the transportation sector is the largest consumer of liquid fuels, which account for 48% of the country's energy consumption. In light of these challenges and the need to achieve the Sustainable Development Goals, various strategies have been proposed to transition towards a more diverse energy mix that reduces dependence on fossil fuels and enhances resilience to climate change (Vita, 2020).

In 2021, an energy auction was held, paving the way for solar and wind projects that will be operational in 2022, raising the contribution of non-conventional sources to 12% (Urrego, 2021). However, there is still a need to increase the share of non-conventional technologies in energy production to ensure the availability and reliability of energy supply. To this end, the Mining-Energy Planning Unit (UPME) has developed the National Energy Plan (PEN) for 2050 (Vita, 2020; Urrego, 2021).

The PEN is based on market projections that take into account historical demand, market expectations, and other variables affecting energy consumption for electricity, gas, and liquid fuels until 2036 (Unidad de Planeación Minero Energética, 2021). The plan proposes four pillars: security and reliability of supply, mitigation and adaptation to climate change, competitiveness and economic development, and knowledge and innovation. The PEN examines four scenarios: upgrade, modernization, inflection, and disruption, with each scenario evaluated in terms of environmental, economic, and energy outcomes (Unidad de Planeación Minero Energética, 2020).

Simulation results show that energy consumption is expected to rise by 48% in the upgrade scenario, 28% in the modernization and inflection scenarios, and 21% in the disruption scenario by 2050. The disruption scenario is the only one that shows a decrease in greenhouse gas emissions (GHGs) despite the rise in energy consumption, but it requires substantial investment in technology. Regardless of the scenario, Colombia is on track to achieve its goal of reducing GHGs by 20% by 2030 under the Paris Agreement (Blum et al., 2021). These findings underscore the importance of greater economic investment, transformation of productive systems, and public policies that align with the energy transition and SDG objectives (Corredor, 2018).

The PEN offers conclusions and recommendations for achieving the objectives under each of its four pillars. Regarding energy supply security and reliability, the report highlights the need for diversification of the energy mix and increased use of local resources. Fossil fuels will continue to play a significant role in the energy mix, but there is a trend towards replacing liquid fuels and firewood with gaseous fuels. In terms of mitigation and adaptation to climate change, the report calls for a move towards carbon-neutrality through technological change, gradual decarbonization of the energy matrix, and development of carbon capture and storage projects.

Finally, for the economic competitiveness and innovation pillars, the PEN proposes significant investments in energy efficiency technologies, evolution of the transport sector towards electric mobility, and energy transformation of the productive sector. These efforts must be accompanied by knowledge management, training of competent human capital, and research and innovation projects aimed at solving technical, environmental, economic, and social challenges of the energy transition (Unidad de Planeación Minero-Energética, 2020; Blum et al., 2021).

Energy transition insights based on bioenergy

The energy transition process outlined in the National Energy Policy (PEN) has established natural gas (NG) as the primary energy source that will gradually decarbonize the energy matrix and enable its electrification. Both NG and liquefied petroleum gas (LPG) are expected to replace liquid fuels and firewood in rural areas (Unidad de Planeación Minero Energética, 2020). However, the role of bioenergy in these scenarios is marginal, and biomass is not being considered as a resource with significant energy potential, despite the availability of this resource with the revival of agroindustry and population growth (Rincón et al., 2018).

Several investigations have been conducted in Colombia to assess the energy potential of biomass and evaluate its technical potential for energy utilization. In 2004, Colombia began implementing bioenergy technologies ahead of its commitments to reduce GHG emissions at COP 21. This foray was made through the production of biodiesel and bioethanol from palm oil and sugarcane, respectively. The goal was to produce B10 (diesel with 10% biodiesel) and E10 (gasoline with 10% bioethanol) blends that were compatible with internal combustion engines (Centro de Información y Documentación Palmero, 2015; Federación Nacional de Biocombustibles, 2019). In 2010, an alliance between academia and the state created the residual biomass atlas, which estimated the theoretical energy potential of different types of residual biomass. The potential of bovine, poultry, and swine residues was highlighted (Table 2) (Ministerio de Minas y Energía, 2015). Subsequently, Law 1715 of 2014 was created, promoting the use of renewable energies and giving greater importance to residual biomass as an alternative source of energy (Rincón et al., 2018). The creation of the National Policy for the Integral Management of Solid Waste (CONPES 3874 of 2016) further emphasized the importance of residual biomass.

Table 1. Theoretical Potential of Livestock Biomass Residual (based on Ministerio de Minas y Energía, 2011; Velásquez & Rincón, 2018)

Biomass residual	Theoretical potential of biomass residual (MW)	
	2010 (UPME, 2011)	2018 (Velásquez & Rincón, 2018)
Poultry	925.4	266.5
Porcine	136.6	131.0
Bovine	2,671.7	2,275.8

With the new policy, biogas acquires importance in Colombia as an energy product from residual biomass. However, both the implementation of technologies for its production, such as anaerobic digestion (AD), and its legislative framework have progressed more slowly than for liquid biofuels. The first uses of AD were for the treatment of urban wastewater, and then business guilds from the pork, poultry, and palm sectors implemented this process for the energy utilization of biogas and digestate (AD byproduct) as a biofertilizer or soil conditioner (Ministerio de Minas y Energía, 2015; Rincón et al., 2018).

In 2016, the Energy and Gas Regulation Commission (CREG) defined the conditions for the integration of biogas into the national energy market through Resolution 240 (Ministerio de Minas y Energía, 2016), allowing for its residential and industrial distribution through the gas network and its transformation into electrical energy, reaching up to 3.95 MW in 2017 (Ministerio de Minas y Energía, 2021). Then, in 2018, a new research report was produced that reports the theoretical and technical (feasible) energy potential of residual biomass in the country for the year 2016. In this report, it was identified that the feasible utilization of poultry waste is 42.8% of its theoretical potential, while for pork and beef, it is only 10.4% and 3%, respectively (Velásquez & Rincón, 2018). Table 2 shows the values of the theoretical energy potential of the national livestock residual biomass for the years 2010 and 2018, estimated from the biogas energy potential they can produce.

These results demonstrate that in rural areas, there is a readily available renewable resource for energy production that would contribute to strengthening the energy transition process, reducing GHGs, properly managing organic waste, and producing organic fertilizers. Furthermore, as established by the National Energy Plan (PEN), if natural gas (NG) is the fuel that will allow the energy transition, biogas and biomethane become its direct substitutes and could prevent a reduction in its existing reserves (Velásquez & Rincón, 2018). Table 3 shows the different uses for raw biogas, biomethane, and digestate according to their enrichment level.

Table 2. Forms of use of biogas, biomethane and digestate

Product	Enrichment level	Components	Impurity removed	Use
Biogas	Raw biogas	Methane, Carbon dioxide, Steam, Hydrogen sulfide		Cooking
	Dry biogas	Methane, carbon dioxide, Hydrogen sulfide	Steam	Cokooing, ilumination
	Purified biogas	Methane, Carbon dioxide	Hydrogen sulfide	Power generation, Cokooing, ilumination
	Biomethane gas	Methane gas	Carbon dioxide	Power generation, Cokooing, ilumination, mobility
	Liquid biomethane	Liquid methane		Power generation, direct sustitution of GNL and GLP, mobility, cooking, ilumination
Liquid Digestate		N, P, K Ca, Mg, Fe, Zn		Fertilization, soil remediation
Solid Digestate	Wet digestate	Water, N, P, K, Ca, Mg, Fe, Zn		Fertilization, soil remediation, fertilizer enrichment
	Dry digestate	N, P, K, Ca, Mg, Fe, Zn	Water	Fertilization, soil remediation, fertilizer enrichment

To optimize the use of biogas and biomethane, it is imperative to fortify the gas pipe-line network in the country and identify the areas with agricultural production that can easily connect to it. A report jointly published by UPME and National University of Colombia in 2018 highlighted that nearby gas pipelines in territories where agricultural pro-duction is carried out can facilitate direct connection, thereby promoting the better distribution of biomethane. The report analysed the level of difficulty in making a satisfactory connection to the pipeline and concluded that the poultry and pig sectors have a high feasibility for network connection due to their intensive production. On the other hand, the bovine sector has medium feasibility because production is more dispersed in the territory (Velásquez & Rincón, 2018).

Biogas, a low-cost technology, can be produced in its raw form and implemented on a small or industrial scale, depending on the residual biomass generated by an agricultural production unit (UPA). This versatility makes biogas a viable alternative to replace fire-wood or liquefied petroleum gas (LPG) for cooking and obtain a by-product with nutrient content that improves soil quality (Roa et al., 2020).

Scaling biogas production at an industrial level can diversify the range of products and services offered by UPAs, sanitary landfills, and wastewater treatment plants, lever-aging the legal framework provided by Law 1715 of 2014 and Resolution 240 of 2016 for the commercialization of biogas and biomethane as fuel or electrical energy (Rincón Martínez et al., 2018).

STUDY SCENARIO

National livestock characteristics

The Colombian livestock sector is a significant contributor to the country's economy and plays a vital role in the Gross Domestic Product (GDP). It encompasses various sub-sectors, such as cattle, pig, sheep, goat, buffalo, horse, and poultry, among others. The cattle, pig, and poultry subsectors have the most significant impact on the Colombian economy and provide a source of income for many rural communities while serving as the foundation for the country's food security. The cattle sector specializes in feedlot and milk production, while the poultry sector focuses on broiler chickens and egg production, and the pig farming sector concentrates on meat production. The cattle, pig, and poultry sub-sectors account for 84%, 8%, and 2%, respectively, of the total livestock production in the country, with a consistent growth trend over the past four years (Rincón et al., 2018; Instituto Colombiano Agropecuario - ICA, 2023).

Antioquia led cattle production with 11.2% of the national total in 2022, followed by Córdoba and Meta, each with 7.8%. In terms of poultry production, Santander and Valle del Cauca were the largest producers, accounting for 24.3% and 19.9%, respectively. Antioquia also led national pork production with 26.5%, followed by Valle del Cauca with 14.7% (Instituto Colombiano Agropecuario - ICA, 2023). These statistics demonstrate that livestock production is concentrated in only 5 out of the 32 departments in Colombia, which are part of the regions with the greatest coverage by the national electric and hydrocarbon networks, allowing productive systems to achieve greater productivity. For instance, Antioquia and Valle del Cauca are two departments with high livestock productivity as reflected in the figures presented. However, regions with limited energy and fuel network coverage have very low livestock productivity, developed in small individual plots in an artisanal way and form part of family economies with limited potential for technological infrastructure improvement and increased productivity. Despite these limitations, the regions with concentrated livestock activity have managed to increase production, surpassing the 2020 total during the first semester of 2022 (Contexto Ganadero, 2022).

Although Colombia is one of the largest beef producers in Latin America, the sub-sector's technological advancement is still in development, and production continues to be mostly extensive, hindering its path towards sustainable and low greenhouse gas emission (GHG) production. Meanwhile, other subsectors such as pig farming and poultry have not closed gaps in investment in technology to achieve higher production and product quality. The main challenges that the sector must overcome to improve its competitiveness are the need to achieve technological advancements that allow for sustainable production meeting international standards, providing appropriate and nutritionally balanced feeding for each species, and conducting research on new technologies and pro-cesses to help increase efficiency and sustainability in production (Becerra et al., 2015; Asociación Colombiana de Porcicultores, 2021).

Moreover, the Colombian livestock sector faces external factors that significantly affect its development, such as variations in rainfall seasons caused by climate change, the increase in the cost and scarcity of fertilizers for animal feed crops, the rise in fuel prices leading to increased transportation costs, and the availability of labor due to the internal conflict of the country and the health crisis generated by COVID-19 (Becerra et al., 2015; Asociación Colombiana de Porcicultores, 2021). To mitigate sectoral issues, the national government has implemented various development plans and legislative frameworks, such as Law 1876 of 2017, seeking to improve production, competitiveness, and sustainability by creating the National Agricultural Innovation System (SNIA). This system has enabled a preliminary diagnosis of the agricultural sector, identifying the need to increase the level of training in agricultural sciences at technical, techno-logical, and professional levels and decentralize educational institutions and research centers to improve coverage throughout the national territory and achieve greater immersion of qualified human capital in the productive chain of the sector (Pedraza &Galvis, 2021).

Energy transition in rural areas

Colombia faces a critical technological challenge: the decarbonization of its energy basket and the transition to an energy matrix with a more significant contribution from renewable energies. The country's agriculture sector, like other productive sectors, relies heavily on fossil fuels and suffers from inadequate infrastructure in rural areas, limiting access to energy resources.

To address this issue, the national government, through the Institute for the Promotion of the Electric Sector for Non-Interconnected Zones (IPSE), has implemented strategies to improve the coverage and reliability of energy services in non-interconnected rural areas. These strategies include the deployment of photovoltaic solar systems alongside tradition-al diesel generator systems. While these efforts have helped provide electricity to rural are-as, the service remains intermittent and costly, negatively impacting the quality of life and economy of the rural population. Moreover, the widespread use of fossil fuels for thermal energy production and cooking, along with the intensive use of firewood, has resulted in increased deforestation, greenhouse gas emissions, and respiratory illnesses among the rural population. To address these challenges, the Colombian government has promoted new strategies such as the installation of efficient kitchens and the exploration of agro-waste biogas production projects, in addition to photovoltaic solar systems (Gaviria et al., 2017; El Colombiano, 2019; Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas - IPSE, 2023a.

However, more work is needed to strengthen these technologies and explore others that allow for the sustainable use of renewable energy sources within the agro-livestock sector's productive chain. Additionally, it is essential to increase the budget for research focused on energy issues for the agro-livestock sector and intensify training and education programs for the rural population to promote the adoption of these and other energy technologies (Gaviria et al., 2017).

RESULTS

National energy matrix in rural areas

The UPME, in collaboration with the National Administrative Department of Statis-tics (DANE), has estimated that electricity coverage extends to over 96% of the total households in the country. However, despite this high coverage, more than 50% of the national territory still lacks electricity connections. Fig. 1 illustrates shaded gray regions that represent areas not connected to the country's national interconnected electricity system (SIN), while white areas represent territories with coverage from the electricity grid. Coverage is concentrated in the Andean and Caribbean regions, where 78% of the population re-sides. The remaining 22% is distributed across the Orinoco, Amazon, and Pacific regions, where the population primarily inhabits rural areas (Unidad de Planeación Minero Energética, 2019; Mesa & Duque, 2021; Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas - IPSE, 2023a).

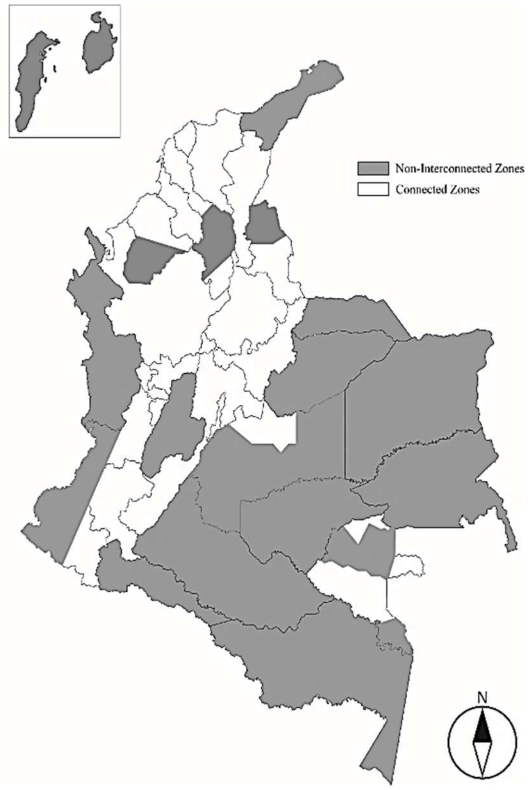

Figure 1. Non-Interconnected Zones in Colombia. The gray areas represent territories not connected to Colombia's electricity grid and the white areas represent territories connected to Colombia's electricity grid (Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas – IPSE, 2023b).

According to the national census presented by DANE in 2018, 15.8% of the population lives in dispersed rural areas, of which 32% are not interconnected to the grid (Departamento Administrativo Nacional De Estadística - Dane, 2018; García et al., 2021; Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas - IPSE, 2023a). This overview of the country's non-interconnection demonstrates the pressing need to increase coverage and reliability in the provision of the electric power service in these regions. To mitigate this issue, the national government, through the IPSE, has developed projects that allow diversifying the energy basket of the Non-Interconnected Zones (NIZ) with renewable energies.

Currently, the installed electric power generation capacity in the NIZs at the national level is supported by 85.4% in diesel and 14.6% in renewable energy technologies (see Fig. 2). The projects in development aim to increase the participation of renewables, evaluating the energy sources of each territory for the implementation of the most appropriate technologies. However, in many territories, the energy solution is hybrid systems with diesel technologies, among which photovoltaic-diesel, SHP-diesel, and biomass-diesel systems stand out, but they only meet part of the demand in the territories where they operate (IPSE, 2023b).

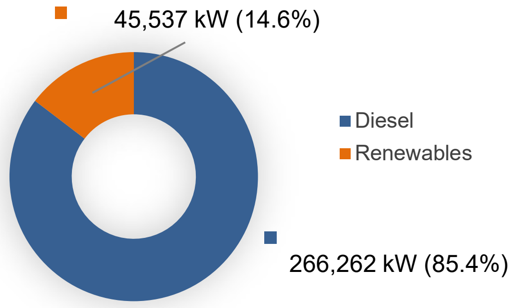

Figure 2. Installed electrical generation capacity in kW for non-interconnected zones (Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas - IPSE, 2023a).

Fig. 3 displays the matrix of renewable energies in NIZs, where individual solar systems (ISSFV) have the highest participation at 69%, followed by centralized solar systems (CSS) at 11%, which include hybrid systems. The low involvement of renewables and the high reliance on diesel for electricity generation highlight the need to prioritize efforts to increase renewable energy inclusion in NIZs, reducing costs by decreasing diesel consumption and ensuring greater coverage and service continuity for different territories. The intermittent nature of the service impacts various economic activities and the quality of life of these populations. In many of these regions, cooling and ventilation systems are required due to high temperatures, as well as electric systems to power educational and health centers, public lighting, and other necessary infrastructure, which cannot operate fully due to the unreliability of the electric utility.

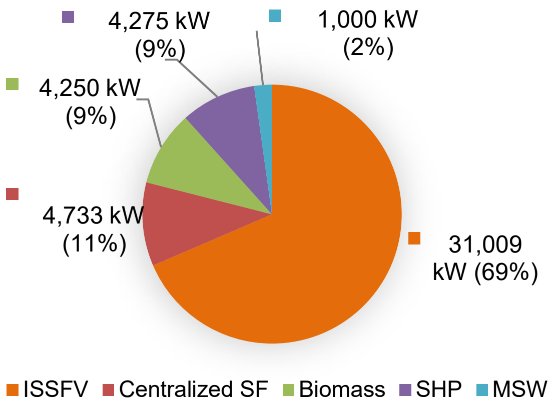

Figure 3. Generation of renewable energies in kW for NIZ. SHP - Small hydroelectric power plant); MSW - Municipal Solid Waste (Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas - IPSE, 2023a; Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas – IPSE, 2023b).

In addressing the need for improved coverage of ZNI electricity service, as well as the desire to increase the use of bioenergy in the energy mix, utilizing biogas as a source of electricity could significantly reduce GHG emissions generated by diesel use. Furthermore, this approach would serve as an effective tool for organic waste management and nutrient recovery for agricultural processes. However, despite the potential benefits, expanding the electricity grid to ZNI areas is a prohibitively expensive undertaking, and the investment recovery period could extend over several years due to the low number of users. To address this challenge, the national government has proposed implementing renewable energy plants near ZNI areas and individual generation systems to help reduce the investment and operating costs of these new systems (Más Colombia, 2022; Vivas, 2023). While this is an interesting alternative, electricity generation should be based on micro and pico power plants distributed throughout these territories. This would ensure that the energy needs of small groups of households can be met, while simultaneously mitigating service delivery problems that are associated with the high dispersion of users.

Over the past two years, the NG network has been expanded and improved. Additionally, the costs of LPG service provision have been reduced, allowing for greater access to both fuels in NIZs. The lower cost access of these fuels for rural households reduces the likelihood of respiratory diseases due to the use of firewood, decreases deforestation, and can improve the productivity of agro-industrial activities. However, the increase in the consumption of NG and LPG also contributes to GHG emissions. While substituting firewood with NG and LPG can reduce public health problems, it also contributes to global warming. Furthermore, the dependence on the price of these fuels in international markets may cause rural households to be unable to afford the fuel if there is an increase in its price, forcing them to return to using firewood and associated problems.

Although the use of NG and LPG can be considered a temporary solution, it is not an effective tool to achieve a fair energy transition in NIZs. It would not allow for sustainable agropastoral processes or the development of an agroindustry capable of achieving a circular economy. Therefore, the inclusion of bioenergy, particularly biogas as a substitute for firewood, NG, and LPG, in rural households and in the productive chain of the agropastoral industry would allow for a focus on more sustainable processes. This would be achieved through the recovery of nutrients for soil and the production of biogas through the utilization of residual biomass. Additionally, environmental benefits could be obtained through the proper management of waste.

Problem with Firewood and Fossil Fuels for cooking in Colombia

The rise in the utilization of natural gas (NG) and liquified petroleum gas (LPG) in rural areas indicates the effectiveness of the national government's approach to discourage the use of firewood (Fig. 4). The strategy involves expanding the coverage of NG and subsidizing the price of LPG. Nevertheless, over one million households continue to depend on firewood as a primary source of energy for cooking. Due to the inefficient and makeshift nature of their kitchens, people are directly exposed to inhalation of particulate matter produced by the combustion of firewood. Household air pollution from firewood and coal use accounts for approximately 2,500 deaths annually in Colombia, as estimated by the National Health Observatory. The majority of these deaths are caused by ischemic heart dis-ease, chronic obstructive pulmonary disease (COPD), acute respiratory infections, cardio-vascular accidents, and lung cancer, as reported by the observatory (Gaviria et al., 2017; El Colombiano, 2019).

In response, the Colombian LPG Association (GASNOVA) introduced LPG as a re-placement for firewood, anticipating that it could reach up to 12 million Colombians with coverage of almost 95% of the national territory, overcoming the challenges of expanding NG services (Rico, 2020). However, the global demand for LPG from China and India resulted in an increase of over 100% in its international price from December 2020 to March 2022. This trend had a direct impact on the domestic cost of the fuel since 5% needed to be imported to meet the national demand. To address this situation, the Colombian government passed law 2128 on August 4, 2021, aimed at subsidizing packaged LPG consumption, cushioning the impact of the international price increase, and avoiding domestic price hikes. The law was intended to close the economic gap that prevented rural populations from accessing this fuel. However, the measures were insufficient, and the price increased by more than 30% in the first months of 2022. This was due to the inability to subsidize 50% and 40% of the final user price for strata 1 and 2, respectively, as established by the law. Instead, only 22% and 18% of the final user price were subsidized for these strata, respectively. Consequently, the price hike led to an 8.6% decline in LPG consumption, causing many rural households to revert to the use of firewood (Gaviria, 2022).

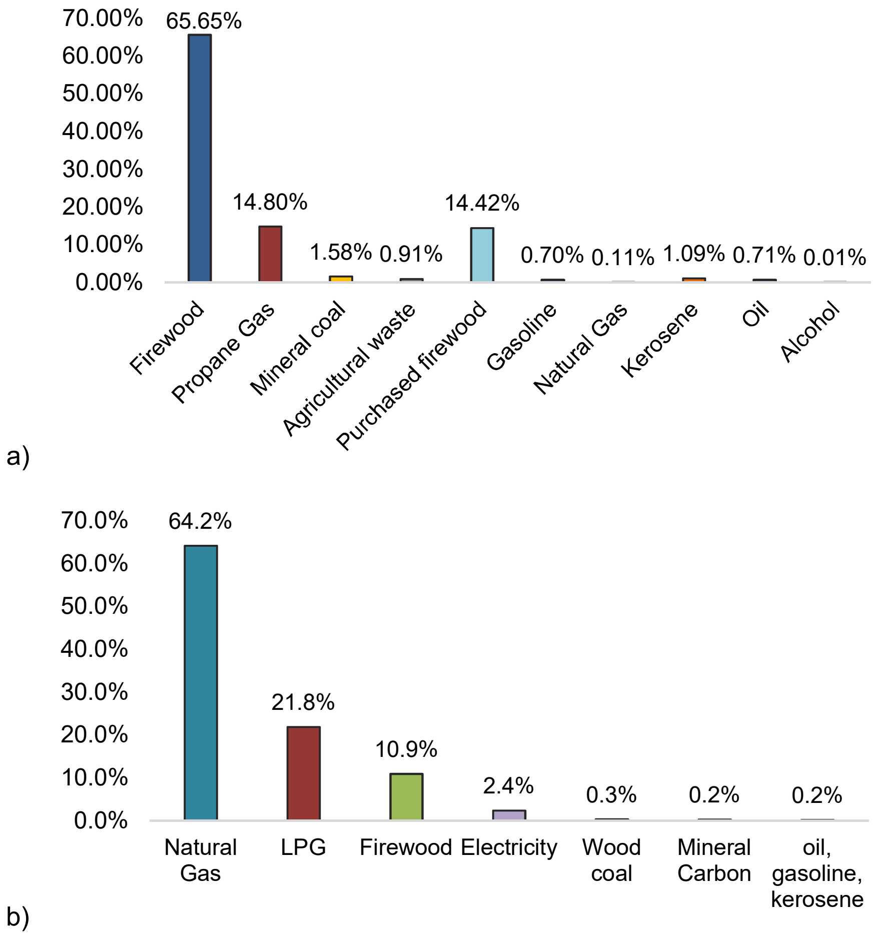

Figure 4. Evolution of the NIZ Thermal Energy Matrix. (a) 2020 and (b) 2022 (Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas - IPSE, 2023a; Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas – IPSE, 2023b).

The aforementioned situation regarding LPG highlights the ineffectiveness of relying on fossil fuels as a heat source in rural areas as a strategy for achieving low costs and improving accessibility and reliability of the service. Relying on subsidies to fossil fuel prices is not a sustainable solution, as these prices are highly volatile and do not guarantee accessibility in the medium to long term. Instead, addressing the cost and coverage of cooking fuels in rural areas should prioritize investments in technologies that allow to produce biofuels with long-term social, environmental, and economic benefits.

Access to energy continues to be a significant challenge in many developing countries, including Colombia, particularly in rural areas where the majority of the population still relies on traditional biomass, such as wood, for cooking and heating their homes. This dependence on biomass not only has health and environmental impacts but also limits the economic potential and quality of life in these regions. However, the production of bioenergy through the utilization of residual biomass can improve access in rural areas, boost productivity in agro-industrial activities, and have a positive impact on the rural economy.Therefore, it is crucial to promote sustainable bioenergy solutions in rural areas. These solutions can involve investments in technologies such as biogas, which allows to produce a clean and affordable cooking fuel using organic waste. Furthermore, in-vestments in efficient cookstoves can significantly reduce emissions of particulate matter generated by the combustion of traditional biomass, which can have severe health consequences for rural populations. By prioritizing investments in sustainable bioenergy solutions, we can improve the quality of life and economic potential in rural areas while simultaneously addressing health and environmental challenges.

Biogas Vs Conventional energy sources

The heavy reliance on fossil fuels for the generation of electrical and thermal energy in the NIZ underscores the pressing need to promote renewable energy sources and eco-friendly substitutes such as biofuels. Among these, biogas, which is derived from an-aerobic digestion of organic waste, presents itself as a viable alternative due to its high methane content and thermal properties that are comparable to natural gas and liquefied petroleum gas.

Studies conducted in Colombia to evaluate the energy potential of residual biomass have shown that the pork industry is well-positioned to leverage 52% of its theoretical potential, whereas the poultry and cattle sectors have only been able to tap into 43% and 1% of their respective potentials (Ministerio de Minas y Energía, 2011; Velásquez & Rincón, 2018). The 'technical potential' here refers to the actual capacity to adopt technologies that facilitate the utilization of residual biomass to produce and distribute biogas through the country's existing gas pipeline infrastructure (Velásquez & Rincón, 2018). Specifically, the pork industry's technical capacity currently amounts to 68.2 MW, which can replace up to 25.6% of the diesel-based electricity production in the NIZs. In contrast, Table 4 shows that biogas production has been stagnating since 2017, and that it only contributes a paltry 5.8% of the total technical capacity that could be harnessed by utilizing pork waste alone.

Based on the data presented in Table 4, it is evident that the demand for electricity has increased in recent years. This conclusion is supported by the fact that the total production of electricity from fuels has increased between 2015 and 2020, accounting for ap-proximately 30% of the country's total electricity demand (Ministerio de Minas y

Energía, 2021). It should be highlighted that coal and natural gas play a significant role in meeting this demand growth.

Table 3. Effective generation capacity by fuel type (MW) (Ministerio de Minas y Energía, 2021)

Year	2015	2016	2017	2018	2019	2020
Diesel	1,247	931	1,248	1,240	926	967
Cane residue	93.2	91.8	130.7	147.7	141.2	141,2
Biogas		2.25	3.95	3.95	3.95	3.95
Coal	1,348.40	1,355.50	1,369	1,727	1,665	1,669
Fueloil	299	187	314	309	272	272
Natural Gas	1,667.45	2,092.95	1,707.95	1,703.30	2,207.40	2,227.80
TOTAL	4,655.05	4,660.05	4,773.60	5,130.65	5,215.55	5,280.50

The significant contribution of fossil fuels in electricity production can be mitigated by utilizing biogas as a direct replacement for these fuels. While the technical capacity to harness the energy potential of livestock waste remains low, and its contribution to the energy matrix may be marginal, a more impactful option is to increase its share in the energy matrix of the NIZs. In this context, biogas can help fulfill the demand for natural gas and LPG for cooking purposes. Assuming a user consumes up to 60 kWh per month of natural gas or LPG, biogas generated from pig waste could potentially meet the energy needs of over 800,000 users, satisfying the demand of the 15,196 families residing in the NIZs (Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas - IPSE, 2023a; Instituto de Planificación y Promoción de Soluciones Energéticas para Zonas No Interconectadas - IPSE, 2023b).

The obtained results indicate that the livestock sector in Colombia holds a significant potential to become a prominent producer of renewable energy. By means of producing biogas and biomethane, this sector could aid in the diversification of the country's electricity and thermal matrix. To achieve this, it is crucial to promote the industrialization of the livestock sector, with a focus on producing these biofuels, which would be facilitated by the current legal framework in the country. This framework allows for a reduction in the implementation costs of renewable energy technologies, injection of biofuels into the gas network, and their commercialization. Hence, centralized biogas production, followed by its transportation and distribution to NIZs, where the gas pipeline system already has coverage, becomes feasible.

Porcine industry characterization

In the past decade, pig production in the country has seen a remarkable average annual growth rate of 9.6%, leading to an impressive 468,880 tons for the year 2020. Despite the various challenges caused by Covid-19, which resulted in the national economy's closure and mobility restrictions, the sector still managed to grow by 5.8% in the following year. The department of Antioquia is responsible for 43% of the country's pig production, contributing 0.8% to the sector's growth in 2020. Cundinamarca is second with 17% of the national production, and Valle de la Cuaca is third with 15.3% (PorkColombia, 2021).

This trend indicates the solidity of the pig production industry, with 75% of the pro-duction concentrated in just three departments, and Antioquia having the greatest potential for waste exploitation due to its productive capacity. However, despite this growth, the percentage of pig farms with advanced technological production processes remains insignificant, and traditional practices in the use of pig waste are still widely maintained. Pig waste is mainly used raw as fertilizer for the growth of pastures in dairy and meat cattle breeding, with no treatment to stabilize the biological load and eliminate pathogens (Roa et al., 2020).

The industry faces several challenges, among which compensating for the high costs of inputs for animal breeding, such as animal food and medicines, stands out. Greater technification of the productive chain and adding value to waste by transforming it and allowing exploration of other markets, such as energy and biofertilizers, could address this challenge (PorkColombia, 2018; López et al., 2020).

The legal framework, particularly Law 1715 of 2014, offers an opportunity to receive tax benefits on the import of technologies for biogas production and its subsequent enrichment into biomethane. This would significantly reduce the implementation costs of the anaerobic digestion process, leading to decreased time for investment recovery. On the other hand, Resolution 240 of 2016 by CREG provides a key tool for introducing biogas and biomethane as energy sources in the Colombian energy market, establishing the necessary technical and commercial conditions for injecting and distributing these biofuels into the natural gas network. This allows for greater diversification of the country's energy matrix and reduced dependence on fossil fuels.

In conclusion, with the continuous growth in productivity in the pork sector and the legal framework in place, there are greater possibilities for developing technically and financially feasible projects to industrialize the sector and enable its access to new markets, such as the energy market, through the production of biogas and biomethane. Additionally, the appropriate utilization of organic waste can provide environmental benefits and the recovery of soil nutrients for reuse in the agricultural industry.

Energy potential from porcine residual biomass production

Intensive pig farming offers an opportunity to effectively collect and utilize pig waste, thereby increasing its technical potential. The use of DA (anaerobic digestion) technology enables proper utilization of pig waste through the production of biogas and stabilized di-gestate, which contains significant nutrient content. From an energy standpoint, the produced biogas can be used to substitute NG and LPG for cooking food. However, given the concentration of pig production in only three departments, it is important to focus the use of biogas on satisfying the energy demand of rural areas near pig farms and incorporating this energy source into the pig production chain, along with the stabilized digestate.

For instance, the department of Antioquia accounts for 43% of the national pig pro-duction and the largest consumer of LPG, where its demand in rural areas corresponds to 17% of the national demand. This makes Antioquia a suitable location for biogas produced from pig excrement to meet its internal demand for LPG. This production model, where the produced biogas is used to replace LPG or NG, could be replicated in other regions of the country, such as Cundinamarca and the Cuaca Valley or in small farms in other territories, to reduce production costs and achieve a circular economy for small pig farmers, where stabilized digestate is also included as an input for agricultural production.

OPPORTUNITIES AND BARRIERS OF CONVENTIONAL FUEL-TO-BIOENERGY SWITCHING

Social

The utilization of swine waste through anaerobic digestion (AD) presents an opportunity for both large and small pig farmers to add more value to their waste by transforming it into a commercial energy source, such as biogas, and a nutrient-rich digestate. However, this productive strategy requires that pig farmers be trained in legal, technical, and economic aspects, and seek alternative partnerships for business growth to generate employment in animal breeding activities, such as operating AD systems.

The possibility of biogas or biomethane reaching ZNI has the potential to revolutionize the lifestyle of many families. Access to reliable and available energy would enable many single mothers to improve their quality of life by utilizing technologies that reduce physical efforts in domestic tasks and allowing them to invest time in their children's education and increase productivity in their economic activities.

However, there is a cultural barrier in the livestock sector, particularly in pig farming, towards the implementation of AD technology. This is primarily due to incorrect designs of AD systems, lack of support from technology providers, and inadequate after-sales ser-vice, as well as a lack of knowledge of the legal framework and the absence of policies that allow for reducing input costs and achieving access to credit for investment in technologies and exploring international markets.

As a result, pig farmers tend to implement AD technology only as a mechanism to stabilize the microbial load of pig manure and comply with the requirements of environmental authorities regarding the use of organic matter in the soil. It is therefore imperative that efforts be made to address these challenges and promote the adoption of AD technology in the livestock sector. This would not only create new business opportunities and promote sustainable agriculture but also contribute to the reduction of greenhouse gas emissions and the mitigation of climate change.

Environmental

In the livestock sector, anaerobic digestion (AD) technology has the potential to mitigate soil and water pollution, reduce the proliferation of vectors, and recover soil nutrients. Furthermore, it enables the recovery of resources from waste, promoting a circular economy approach that reduces the need for external inputs and results in cost savings and reduced greenhouse gas (GHG) emissions. Additionally, the production of stabilized digestate positively impacts soil fertility and reduces the need for synthetic fertilizers, which can have negative environmental consequences.

However, implementing AD technology in rural areas remains a challenge in Colombia. The lack of strict enforcement of environmental regulations and inadequate waste management practices can lead to soil and water pollution and unpleasant odors in near-by areas. Additionally, the use of raw excrement, especially pig waste, can lead to soil degradation and the transmission of diseases through the vectors that these materials car-ry. These issues highlight the need for effective regulation and policies to encourage proper management of livestock waste, including the promotion of AD technology, and the need for education and training programs to ensure the correct operation and maintenance of AD systems.

In summary, the use of AD technology in the management of livestock waste offers numerous benefits, including mitigating environmental impacts, reducing GHG emissions, and cost savings. However, the challenges associated with its implementation, including inadequate waste management practices and a lack of regulation, must be ad-dressed to ensure successful adoption of AD technology in rural areas of Colombia.

Economic

Biogas and stabilized digestate are highly valuable products that present opportunities to explore new markets in the livestock sector, achieve sustainable processes through waste utilization, and enhance the competitiveness of livestock products in various markets. In addition, circular processes can be implemented to reduce costs, where biogas and biofertilizers can be integrated into the production chain.

However, successful implementation of anaerobic digestion (AD) technology requires more than simply installing a digester. It necessitates a comprehensive understanding of the legal, technical, and economic aspects of the technology, as well as identifying alternative partnerships and business models that can support its growth. The lack of knowledge and resources in these areas has been identified as a significant barrier to the widespread adoption of AD technology in the pig farming industry.

Furthermore, economic barriers such as the high cost of inputs for livestock production, difficulties for small farmers to access credit, and the country's road infrastructure pose significant challenges to the sector's growth. To overcome these challenges, there is a pressing need for education and training programs that can equip pig farmers with the knowledge and skills to operate and maintain AD systems effectively. Policymakers and industry leaders must collaborate to create a supportive regulatory framework that provides incentives for pig farmers to invest in AD technology, such as reducing input costs and facilitating access to credit for technology investment and exploring international markets. This would help to foster greater economic growth in the sector and reduce the dependence of farmers on external sources of energy and fertilizer while improving the quality of their soil.

In conclusion, the adoption of AD technology in the management of livestock waste has enormous potential, but its successful implementation requires the development of appropriate regulatory frameworks, education and training programs, and innovative business models to enable farmers to reap its full benefits.

CONCLUSIONS

The anaerobic digestion of livestock waste is a promising solution for renewable energy production and mitigating environmental issues associated with improper waste management. In Colombia, the transformation of livestock waste into biogas presents significant energy potential, contributing to the country's energy transition and the decarbonization of rural areas. The pig farming sector, particularly in the Antioquia department, boasts the greatest technical potential for energy utilization of its waste, leading towards a circular economy.

The expansion of the gas network in non-interconnected zones (ZNI) now allows for the injection of biogas and biomethane into this network, making it possible to supply these biofuels to users in these zones, even if biogas production occurs in regions different from consumption. With the Antioquia, Valle del Cauca, and Cundinamarca departments being major pig farming regions, the sector can utilize the gas network for the transportation and commercialization of biogas and biomethane in ZNI, where there is an unsatisfied demand for this type of energy.

Anaerobic digestion technology offers an alternative for the industrialization of the live-stock sector and a tool for this sector to become a relevant actor in the Colombian energy market. By utilizing this type of livestock waste, the sector can directly engage in sustainable processes and approach the development of a circular economy. This energy production model can be replicated in developing countries that still rely on traditional biomass to meet their thermal energy needs.

While social, environmental, and economic barriers still exist for biogas to acquire a greater share in the Colombian energy matrix, these can be overcome through public policies that allow for increased productivity in the agricultural sector and its linkage to new energy markets, taking advantage of the existing regulatory framework for renewable energy and biogas. The social, environmental, and economic opportunities and benefits that come with the energy utilization of agricultural residual biomass make biogas an ideal energy source for achieving an effective and fair energy transition, particularly in rural areas and ZNI that have had their basic needs unmet for many years.

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