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Application of productive strategies to replace internal combustion engines with electric ones in "ASOMUNUE", Mariscal Sucre parish, Milagro.

Aplicación de estrategias productivas para sustituir motores de combustión interna por eléctricos en "ASOMUNUE", parroquia Mariscal Sucre, Milagro.

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Abstract.
The transition towards cleaner and more sustainable energy sources has become a priority in various sectors, especially in agriculture, where internal combustion engines play an important role in irrigation operations. These engines, while functional and widely used, generate significant greenhouse gas emissions and rely on fossil fuels, thus contributing to global warming and environmental degradation. In this context, replacing these engines with electric systems connected to distribution networks with transformers offers an innovative and environmentally responsible solution. This article analyzes the technical and economic aspects of this transition, highlighting the benefits that include a notable reduction in carbon emissions, lower long-term operational costs, and decreased noise pollution. Additionally, it addresses the associated challenges, such as the need to install adequate electrical infrastructure, ensure energy supply stability in rural areas, and adapt irrigation systems to the new motors. This approach not only promotes eco-efficiency but also strengthens agriculture's commitment to sustainable development.

Keywords.
Agriculture, Environmental Pollution, Global Warming, Internal Combustion Engines, Sustainable Energy.

Resumen.
La transición hacia fuentes de energía más limpias y sostenibles se ha convertido en una prioridad en diversos sectores, especialmente en la agricultura, donde los motores de combustión interna desempeñan un papel importante en las operaciones de riego. Estos motores, aunque funcionales y ampliamente utilizados, generan emisiones significativas de gases de efecto invernadero y dependen de combustibles fósiles, contribuyendo así al calentamiento global y al deterioro ambiental. En este contexto, el reemplazo de estos motores por sistemas eléctricos conectados a redes de distribución con transformadores ofrece una solución innovadora y ambientalmente responsable. Este artículo analiza los aspectos técnicos y económicos de dicha transición, destacando los beneficios que incluyen una notable reducción de las emisiones de carbono, menores costos operativos a largo plazo y una disminución de la contaminación sonora. Asimismo, se abordan los desafíos asociados, como la necesidad de instalar una infraestructura eléctrica adecuada, garantizar la estabilidad del suministro energético en áreas rurales y adaptar los sistemas de riego a los nuevos motores. Este enfoque no solo promueve la ecoeficiencia, sino que también fortalece el compromiso de la agricultura con el desarrollo sostenible.

Palabras clave.
Energía Sostenible, Agricultura, Motores de Combustión Interna, Calentamiento Global, Contaminación Ambiental.

Keywords.
Agriculture, Environmental Pollution, Global Warming, Internal Combustion Engines, Sustainable Energy.

1.- Introduction

Agriculture is one of the sectors that consumes the most natural resources and, in turn, one of the sectors that contributes the most to the emission of greenhouse gases, particularly through the use of internal combustion engines in irrigation systems. These engines, which run primarily on fossil fuels such as diesel or gasoline, have been a traditional solution for farm irrigation due to their ability to operate in remote areas. However, its negative impacts on the environment and rising fuel costs raise the need to look for more sustainable alternatives. In this context, the replacement of internal combustion engines with grid-connected electric motors with transformers emerges as an efficient and environmentally friendly alternative.

This change not only represents a technological advance in the sector, but also an opportunity to reduce the carbon footprint of agriculture, optimize operating costs, and improve the quality of life of agricultural producers by eliminating noise pollution and simplifying equipment maintenance. This article explores in detail the benefits of this transition, such as reducing greenhouse gas emissions and harnessing sustainable electrical energy, as well as technical challenges, such as adapting electricity infrastructure in rural areas and the initial investments

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required. In addition, key considerations are presented to implement this solution effectively, positioning agriculture as a key player in the fight against climate change and the adoption of eco-efficient practices.

1.1.- Context and relevance:
This research project refers to the installation of an electrical system for the operation of a submersible pump for the irrigation system in a 7-hectare farm called Hacienda Emanuel Los Palmares, Province of Guayas, on the outskirts of Mariscal Sucre, Milagro. UTM coordinates: 667810.20 m E; 9768632.65 m S

The distance from the distribution pole to the well is 60 meters, with a pole installation perimeter near the well of 15m. The irrigation system will be distributed in pipes of 8 to 10 inches in diameter, with a separation between each irrigation system of 8 to 10 meters.

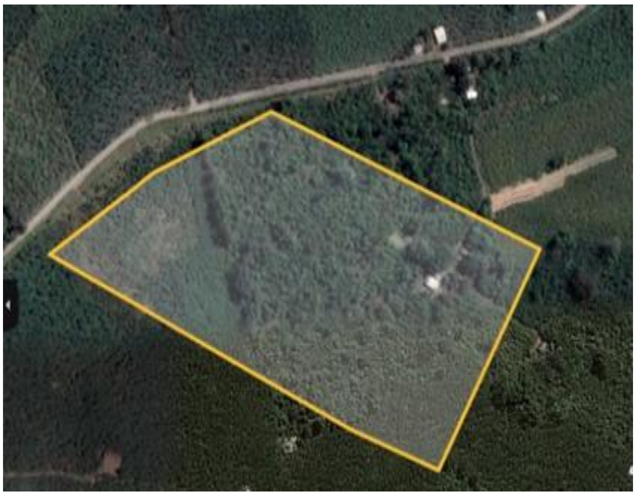

Figure 1: Aerial view of the Hacienda. **Source:** Google Earth.

1.2.- State of the art:
Moving towards a sustainable energy transition in rural environments represents a key strategy to mitigate climate change and reduce structural inequalities in access to energy services. Various scientific studies agree that the replacement of fossil fuel-based technologies with low-emission electricity systems can generate far-reaching environmental, economic and social benefits, especially in energy-poor communities.

In this context, recent research has shown that: "Sustainable energy transitions based on renewable sources have been shown to significantly reduce the per capita carbon footprint in regions with high levels of energy poverty". This statement is aligned with the objectives of this study, which proposes the change of diesel engines for three-phase electric motors in the agricultural irrigation system of the ASOMUNUE association.[1]

In addition, it has been found that: "Decentralized renewable technologies can provide basic access to electricity at a fraction of the cost of grid extensions." This reinforces the technical and financial feasibility of using electric motors in the agricultural sector, as an efficient alternative to internal combustion systems.[2]

Likewise, although this study focuses on irrigation systems, the principles of energy efficiency are applicable in multiple rural areas. For example: "Energy-efficient cooking technologies, such as improved stoves, can reduce the carbon footprint by up to 70% compared to traditional methods based on unsustainable biomass." This comparison illustrates how energy efficiency represents a cross-cutting mechanism for environmental mitigation in rural environments.[3]

Beyond the climate aspect, access to clean technologies also translates into health benefits. In fact, "The lack of access to clean energy increases exposure to indoor pollutants, affecting respiratory health." This justifies from an environmental justice perspective the replacement of polluting motors with electric solutions, such as the one proposed in ASOMUNUE.[4]

However, energy sustainability is not without its challenges. Some studies warn about the trade-offs between carbon and water, as "Solar expansion reduces carbon, but can significantly increase water consumption in arid areas". In this sense, life cycle assessment (LCA) becomes essential to evaluate cross-impacts. In this article, LCA is used to calculate avoided emissions, and efficient water management is promoted through the optimization of the electrified irrigation system.[5][6]

This integration of sustainable technology in rural contexts, such as ASOMUNUE, is part of a global trend. "Sustainable energy transitions have been documented to have significantly reduced the per capita carbon footprint in regions with high levels of energy poverty." Added to this is the evidence that "climate-smart agricultural practices also improve energy efficiency and reduce water demand" [7][8]

In addition, the implementation of "Well-designed rural microgrids can improve energy access and reduce carbon footprint if they are based on local renewable sources" [9]

However, the need for this transition becomes even clearer if the negative effects of the fossil fuel-based energy model are considered. For example, in Somalia it has been shown that **The** "Energy consumption has a significant and positive effect on long-term carbon emissions in Somalia, indicating that the increase in energy currently used in the country is not environmentally sustainable" [10]

A similar conclusion has been evidenced in Malaysia, where it is confirmed that the prolonged use of non-renewable energy maintains a significant relationship with the increase in CO_2 emissions, reinforcing the need to

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migrate to cleaner sources and more efficient technologies [11]

The objective of this research is to analyze the technical, economic and environmental feasibility of replacing internal combustion engines with electric motors in the irrigation systems of the New World Production Association (ASOMUNUE), located in the Mariscal Sucre parish of the Milagro canton, in order to promote sustainable and eco-efficient agricultural practices.

Local contextualization in small-scale agriculture: most studies focus on vehicles or industrial machinery, but few analyze irrigation systems in rural associations such as ASOMUNUE. This work provides a specific territorial and community approach, correcting the lack of evidence for similar areas in Ecuador.

- **Contributions:**

Applied technical contribution: The study presents the design and implementation of an electric pumping system adapted to a 7-hectare farm, using electric motors to replace diesel engines. This includes detailed calculations of energy demand, transformer selection, wiring, connections and grounding systems, which constitutes a practical contribution applicable in similar agricultural contexts in Ecuador and Latin America.

Economic contribution: An exhaustive comparison is made between the operating costs of internal combustion engines and electric engines. The study shows a significant reduction in monthly costs (from more than $1,000 to about $320), providing clear evidence of sustainable economic savings for small and medium-sized agricultural producers.

Environmental contribution: A 90% reduction in CO_2 emissions is demonstrated by replacing traditional motors with electric ones, which represents a mitigation of approximately 6.6 tons of CO_2 equivalent per year. This data is key for sustainability and energy transition policies in the agricultural sector.

Strategic and social contribution: The study promotes the fulfilment of the Sustainable Development Goals (SDGs), especially SDGs 7 (affordable and clean energy) and 13 (climate action), positioning agricultural associations such as ASOMUNUE as active actors in the fight against climate change.

Contextualized innovation: Unlike more generalist international studies, this work integrates real technical data, Ecuadorian regulations and local needs, becoming a reference guide for the implementation of clean energy solutions in rural areas of the country.

1.3.- Energy problems in agriculture and energy poverty.

The development of sustainable agriculture requires a radical transformation in the energy sources used in rural areas, especially those that rely on internal combustion engines. Not only do these systems generate high levels of greenhouse gas (GHG) emissions, but they also involve high operating costs and dependence on fossil fuels. This problem particularly affects peasant communities that face energy poverty, technological exclusion and economic limitations to migrate towards clean energy solutions.[12]

Agriculture, especially in rural areas, historically relies on internal combustion engines for critical tasks such as irrigation. These systems, although functional, present a double problem: on the one hand, they generate significant greenhouse gas (GHG) emissions, contributing to climate change; on the other, they imply high operating costs due to the volatility of fossil fuel prices. This technological dependence limits the competitiveness of small producers and increases their vulnerability to energy and environmental crises.

Energy poverty in rural environments aggravates this situation. According to recent studies, more than 30% of farming communities in developing countries lack reliable access to clean energy, restricting the adoption of modern technologies and perpetuating economic exclusion. This deficiency not only affects agricultural productivity, but also quality of life, by increasing health risks due to exposure to pollutants and reducing development opportunities. In this context, agricultural electrification emerges as a key strategy to break the cycle of fossil dependency and energy poverty, offering sustainable solutions that integrate efficiency, resilience and equity.[13]

1.4.- Energy transition and environmental benefits.

Sustainable energy transitions based on renewable sources have been shown to significantly reduce the per capita carbon footprint in regions with high levels of energy poverty. Various studies have shown that rural microgrids powered by local renewable sources (such as solar or wind) not only improve energy access, but also reduce the environmental impact associated with conventional technologies.[14]

In addition, decentralized technologies allow solutions adapted to the context, with lower implementation costs than traditional electricity grid extensions. This approach has been supported by national and international strategies that promote the use of clean energy to meet the Sustainable Development Goals (SDGs), especially SDG 7 (affordable and clean energy) and SDG 13 (climate action).[15]

The transition to electricity systems in agriculture represents a structural change with positive environmental impacts. Replacing diesel engines with electric motors drastically reduces CO_2 emissions, especially in countries whose energy matrix is based on renewable sources, such as Ecuador. In addition, this transition decreases noise pollution and the risk of fuel spills, contributing to the protection of local ecosystems. From a global perspective, agricultural electrification aligns with the Sustainable Development Goals (SDGs), particularly SDG 7 (affordable

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and clean energy) and SDG 13 (climate action), consolidating agriculture as a relevant actor in climate change mitigation.[16]

1.5.- Environmental assessment tools: Life Cycle Assessment (LCA).
A key element in the environmental assessment of these energy solutions is the Life Cycle Assessment (LCA), which allows quantifying the impacts from production to final disposal of the technological systems used. Through LCA, the main critical points of environmental impact are identified, including emissions, resource consumption, waste generation and water use. The water footprint, for example, becomes relevant in arid areas where certain solar thermal solutions can generate pressure on water resources.[17]

Life Cycle Assessment (LCA) is an essential methodological tool for assessing the environmental impact of energy technologies. It allows quantifying emissions, resource consumption and waste generation from manufacturing to final disposal, offering a comprehensive view of environmental performance. In the agricultural context, LCA is critical to compare fossil and electric technologies, identifying critical points such as carbon footprint and water footprint, which are decisive in areas with water stress.[18]

Applying LCA in agricultural electrification projects not only validates the reduction of emissions, but also anticipates indirect impacts, such as water consumption in solar thermal solutions or the generation of electronic waste. This holistic perspective allows for the design of complementary mitigation strategies, ensuring that the energy transition is truly sustainable. In addition, LCA facilitates evidence-based decision-making, supporting public policies and business models oriented towards the circular economy and environmental resilience.

1.6.- Impacts on public health and clean technologies.
From a public health perspective, the lack of access to clean energy also increases exposure to indoor pollutants due to the use of unsustainable biomass, especially affecting women and children. Technologies such as improved stoves make it possible to reduce the carbon footprint generated by traditional cooking methods by up to 70%.[19]

Lack of access to clean energy in rural communities not only limits agricultural productivity, but also creates significant public health risks. The prolonged use of fossil fuels and biomass in agricultural and domestic processes increases exposure to indoor pollutants, such as particulate matter and toxic compounds, which affect the respiratory and cardiovascular systems. These impacts are more severe in women and children, who are usually more exposed to contaminated environments during daily work.

The adoption of clean technologies, such as electric motors and efficient irrigation systems, contributes to reducing these negative externalities. By eliminating the direct combustion of diesel, the emission of harmful particles and gases is reduced, improving air quality in agricultural environments. In addition, electrification makes it possible to integrate complementary solutions, such as automated irrigation systems, which reduce human contact with fuels and reduce occupational risks. This technological change, therefore, not only has environmental benefits, but also positive repercussions on the health and well-being of rural communities.

1.7.- Justification for the ASOMUNUE case.
In contexts such as ASOMUNUE, where agricultural production depends heavily on motor pumps with internal combustion engines, there is an urgent need to migrate to efficient electric technologies. This transition not only responds to a logic of environmental sustainability, but also to the reduction of operating costs, reduction of fire risk, improvements in occupational health and alignment with rural electrification policies promoted by the State.[20]

In developing countries, such as Somalia and Malaysia, studies have confirmed that non-renewable energy consumption has a significant correlation with the increase in CO_2 emissions, showing that current energy models are not sustainable in the long term.[21]

The ASOMUNUE association represents an emblematic case for the implementation of clean technologies in Ecuadorian agriculture. Its location in a rural area with limited access to conventional energy infrastructure and its historical dependence on diesel engines for irrigation make it an ideal scenario to assess the technical and economic feasibility of electrification. In addition, the local context reflects common challenges in other farming communities in the country, such as high operating costs, vulnerability to fluctuations in fuel prices, and the need to comply with environmental regulations. Therefore, this study not only provides specific solutions for ASOMUNUE, but also generates replicable evidence for public policies and sustainable rural development projects.[22]

1.8.- Comprehensive strategic perspective.
The incorporation of clean energy solutions in rural areas is a strategic necessity to guarantee resilient, inclusive and low-emission agricultural production, based on technical and scientific evidence. This energy transition, evaluated through tools such as LCA, must be promoted from a comprehensive vision that articulates economy, environment and social justice to achieve a balance between development, health and sustainability in rural territories.[23]

The transition to electricity systems in agriculture must be conceived as part of a comprehensive strategy that articulates technical, economic, social and environmental dimensions. It is not enough to replace engines; It is necessary to guarantee the availability of electricity infrastructure, design accessible financing schemes and promote the training of farmers in the use and maintenance of new technologies. This holistic vision ensures that electrification is not limited to technological change, but becomes a catalyst for inclusive and resilient rural development.

From a public policy perspective, agricultural electrification can be integrated into national energy transition and climate change mitigation programs. Its implementation contributes to the fulfillment of international commitments, such as the Paris Agreement, and strengthens the competitiveness of the agricultural sector. In addition, by reducing dependence on fossil fuels, vulnerability to global energy crises is reduced, consolidating the country's food and energy security. In this sense, agricultural electrification is not only a technical solution, but a strategic tool to achieve sustainability and social equity goals.

2. Materials and methods.

For the implementation of the electric irrigation system on the farm "Hacienda Emanuel (Los Palmares)", the following materials and equipment were used:

2.1.- Description of materials and equipment:

Electric submersible pump from 7 to 10 HP, Franklin Electric model, approximately 80% efficiency.
30 kVA three-phase transformer (ABB® brand), with primary voltage of 7.2 kV and secondary voltage of 220 V.
CONC type overhead electrical conductor . AL. 2×6+6MM² (6 AWG XLPE) XLPE, made of aluminum.
8- to 10-inch diameter high-density polyethylene (HDPE) pipe for irrigation system.
Pop-up sprinklers model 8005 – 8000 Series, with flow rates from 0.86 to 8.24 m³/h and radii from 11.9 to 24.7 m.
Grounding system, consisting of 5/8" x 1.8 m Copperweld rod and #10 AWG conductor.
Energy meter type 2F-3H, KWH, class 100, terminal block.
Software used: **Microsoft Excel** for comparative analysis of costs and emissions, and **AutoCAD** for electrical design.

2.2.- Experimental design:

An applied descriptive-comparative study was designed, focused on the replacement of an agricultural irrigation system based on internal combustion engines (diesel) with a system powered by electric motors connected to the three-phase grid.

Variables measured:

- Monthly and annual energy costs.
- Fuel consumption (diesel) and electricity (kWh).
- Scheduled maintenance of equipment.
- CO_2 emissions (kg/month and kg/year).

Controlled variable:

Water flow required for uniform irrigation over 7 hectares.

2.3.- Procedures:

- **Initial diagnosis**: The current energy and operational situation of the farm was identified, including location of the well, type of diesel pump and water distribution system.
- **Design of the electrical system**: The electrical demand was calculated based on the power of the pump and the appropriate three-phase transformer was selected.
  The distribution network was designed from the nearest pole (60 m away) to the point of consumption.
  The elements of protection, measurement and grounding were defined.
- **Technical-economic and environmental comparison**: The monthly energy consumption of both systems (electric vs. combustion) was estimated.
  The CO_2 emission factor of the National Interconnected System of Ecuador (0.09 kg CO_2/kWh) was applied.
  Monthly energy, maintenance, and operating costs were calculated.
- **Validation of the proposed system**: Regulations from the IEEE, NEC, NEMA, MEER and CNEL were analyzed.
  Compliance with technical standards was reviewed through load simulation and verification of electrical diagrams.

2.4.- Data analysis:

The comparative analysis between the two pumping systems was carried out using:

- **Microsoft Excel** for energy consumption, costing, and emissions estimation.
- **Tables of emission factors** published by the Ministry of Energy and Mines of Ecuador.
- The analysis was presented in comparative tables that include monthly and annual values and percentages of economic and environmental savings.

3. Analysis and Interpretation of Results.

1. **Presentation of results:**
   Decentralized renewable technologies can provide basic access to electricity at a fraction of the cost of grid extensions [24]

The results obtained focused on three main dimensions: the technical analysis of the electric irrigation system, the comparison of operating costs between the internal combustion engine and the electric motor, and the environmental assessment based on CO_2 emissions.

Table 1. Cost comparison between internal combustion pump and electric motor (80 h/month)

Appearance	Internal combustion pump	Electric pump 10 hp
Initial Pump Cost	$3,500	$2,800
Monthly energy cost	$153.44	$33.42
Monthly maintenance	$120 – $150	$40 – $60
Estimated Total Monthly Cost	$1,020 – $1,050	$302.50 – $322.50

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Estimated Annual Cost	\$12,240 – \$12,600	\$3,630 – \$3,870

Source: Own elaboration

Carbon footprint reduction.
Internal combustion engine
Calculating the carbon footprint when replacing internal combustion engines with electric motors involves analyzing the CO_2 emissions that are from the use of fossil fuels and comparing them with the emissions derived from the generation of electricity consumed by electric motors. [25]

Fuel emission factors (kg CO_2 per litre):

- Diésel: 2.68 kg de CO_2 por litro.
- Gasolina: 2.31 kg de CO_2 por litro.
- Diésel: 10.14 kg de CO_2 por galón.
- Gasolina: 8.75 kg de CO_2 por galón.

Calculation: $\text{Consumo mensual en litros} = 59.89\text{galones} \times \frac{3.785\text{litros}}{\text{galón}}$

$$\text{Consumo mensual en litros} = 226.68\ \text{litros/mes}$$

Emisiones Mensuales de CO_2

$$\text{Consumo de combustible (litros/mes)} \times \text{Factor de emisión (kg de } CO_2\text{/litro)}$$

$$\text{Emisiones mensuales (kg } CO_2) = 226.63\text{litros} \times 2.68\text{kg } CO_2\text{/litro}$$

$$\text{Emisiones mensuales (kg } CO^2) = \mathbf{607.51kg\ CO_2/mes}$$

Emisiones Anuales de CO_2

$$\text{Emisiones anuales (kg } CO_2) = 607.51\text{kg } CO_2\text{/mes} \times 12$$

$$\text{Emisiones anuales (kg } CO^2) = \mathbf{7,290.14\ kg\ CO_2/year}$$

In Ecuador, the CO_2 emission factor of the National Interconnected System (SNI) has been determined at 0.09 tons of CO_2 per , equivalent to $\text{megavatio} - \text{hora} (tCO_2/MWh) 0.09\ \text{kg de } CO_2 \text{ por kilovatio} - \text{hora} (kgCO_2/kWh)^1$

Electric motor

$$\text{Emisiones mensuales (kg } CO^2) = \text{Consumo eléctrico (kWh)} \times \text{Factor de emisión (kg } CO_2\text{/kWh)}$$

$$\text{Emisiones mensuales} = 569.8\text{kWh} \times \frac{0.09\text{kg } CO^2}{\text{kWh}}$$

$$\text{Emisiones mensuales} = \mathbf{51.282\ kg\ CO_2/mes}$$

$$\text{Emisiones anuales} = 51.282\text{kg } CO_2\text{/mes} \times 12 = \mathbf{615.38kg\ CO_2/year}$$

Table 2. CO2 emission comparisons

Engine	Monthly emissions (kgCO2)	Annual emissions (kgCO2)
Diesel Engine	607,51	7290,14
Electric motor	51,282	615,38
Percentage reduction		90%

Source: Own elaboration

Off-grid renewable energy systems generate 60-90% fewer emissions compared to traditional diesel generators in rural areas.[26]

With an emission factor of 0.09 kg CO_2/kWh, the electric motor generates 615.38 kg of CO_2 per year, while the combustion engine generates 7,290.44 kg of CO_2 per year. This represents a reduction of approximately 90% in CO_2 emissions, equivalent to avoiding 6.6 tons of CO_2 equivalent per year.

Analysis of results:
The data reveal a clear economic and environmental advantage of using electric motors:

- **Cost reduction**: the change in technology represents a savings of approximately 70% in monthly operating costs. These savings are attributed to the lower price per kWh (\$0.056) compared to a gallon of diesel (\$1.50), and lower maintenance costs and elimination of oil change.
- **Longer service life**: electric motors have an average useful life of 10 to 15 years compared to 5 to 8 years for combustion engines.
- **Emission reduction**: a 90% decrease in CO_2 emissions was obtained, representing a reduction of 6,675 kg CO_2/year (6.6 tonnes).

Interpretation of results:

- The results are aligned with the objectives of the study: to demonstrate the technical, economic and environmental feasibility of replacing internal combustion engines in rural agricultural areas of Ecuador. The magnitude of energy savings and emission reductions confirm the relevance of the proposed change, especially in a context where the country's energy matrix has low emissions thanks to its high hydroelectric component.
- From the theoretical framework, the study confirms that the electrification of agricultural processes contributes significantly to the fulfillment of the Sustainable Development Goals (SDGs 7 and 13), as well as to improving working conditions, reducing dependence on fossil fuels, and promoting clean technologies in traditionally carbon-intensive sectors.

Limitations and biases:

- **Limited geographic scope**: The study was conducted on a single farm, limiting immediate generalizability of the results to other regions or agricultural conditions.
- **Estimated consumption data**: although actual technical parameters were used, energy and emissions data are based on average operating estimates (80 hours/month), which may vary depending on the irrigation usage regime.
- **Dynamic costs**: both the electricity tariff and the price of diesel are subject to market variations, which can alter the cost relationship in the future.

- **Lack of direct social assessment**: social impacts such as farmers' perception of technological change or cultural barriers to implementation were not measured.

4. Discussion.

4.1.- Interpretation of the results:

The results of the study show that the replacement of internal combustion engines with electric motors in agricultural irrigation systems represents a viable, economically and environmentally responsible alternative. This finding is directly aligned with the objectives set, which sought to analyze the technical, economic and environmental feasibility of this transition in the ASOMUNUE Association. The 90% reduction in CO_2 emissions, coupled with savings of more than 70% in operating costs, demonstrates that the adoption of electric technologies can have a significant impact on both environmental sustainability and profitability for agricultural producers.

"Off-grid hybrid systems showed a 70–90% reduction in global environmental impacts, including carbon footprint, water footprint, and human toxicity." [27]

From the theoretical framework, these results support the postulates on eco-efficiency in agriculture and reinforce the importance of the energy transition to mitigate climate change, especially in countries with a clean energy matrix such as Ecuador.

4.2.- Comparison with previous studies:

The findings are consistent with research by organizations such as the , which highlight the need to reduce emissions in agriculture through clean technologies. In addition, studies such as the one by highlight the role of electrification in reducing the carbon footprint in the productive sector. Unlike these studies, which tend to focus on theoretical models or on different regions, this paper applies the concepts to a practical case, contextualized in a rural Ecuadorian area, with real measurements of consumption and costs, which strengthens its local relevance and immediate applicability.[28][29]

Likewise, this study responds to a gap identified in the literature: the limited availability of specific technical-economic analyses for agricultural production associations in developing countries. By integrating electrical design, cost assessment, and emissions analysis, the work contributes significantly to this underexplored area. [30]

4.3.- Theoretical and practical implications:

From a theoretical point of view, the results validate conceptual frameworks related to energy efficiency, technological transition and rural sustainability. It is shown that it is possible to adopt clean technologies in agricultural contexts without compromising productivity, and even improving operational efficiency.

Energy consumption contributes positively to economic growth, but it also intensifies environmental pollution, which requires sustainable energy strategies.[31]

On a practical level, the study offers a replicable model of electrification of irrigation systems that can be adopted by other associations or small agricultural farms. Implications for the industry include:

- Reduction of operating costs in agribusiness.
- Increase in the useful life of the equipment.
- Improved compliance with environmental and energy regulations.
- Possibility of integration with renewable energy sources (solar, hydro).
- In addition, the results can be used as a basis for public policies aimed at promoting agricultural electrification and sustainable rural development.

4.4.- Limitations and recommendations:

Among the main limitations of the study are:

- **Limited scope of the case study**: it focuses on a single farm, which restricts the generalization of the results to other regions or scales of production.
- **Energy and cost estimates**: Although based on actual parameters, consumption and maintenance data may vary depending on specific use, ground conditions, or market fluctuations.
- **Lack of social and cultural analysis**: A qualitative assessment of farmers' acceptance of technological change, or social or knowledge barriers that could hinder its implementation, was not included.

4.5.- Recommendations for future research:

- Expand the study to more farms and regions of the country to validate the results in different agro-productive contexts.
- Include multi-criteria analyses that integrate technical, economic, social and environmental factors.
- Incorporate renewable energy sources (such as solar photovoltaic) to strengthen rural energy autonomy.
- Develop longitudinal studies that measure the impact of technological change in the medium and long term.

5.- Conclusions.

Summary of findings

This study showed that the replacement of internal combustion engines with electric motors in agricultural irrigation systems on the farm "Hacienda Emanuel (ASOMUNUE)" allows to significantly reduce operating costs and polluting emissions. Key results include a 70% reduction in monthly operating costs and a 90% decrease in CO_2 emissions, equivalent to avoiding approximately 6.6 tons of carbon dioxide annually. These findings are fully aligned with the objectives of the study, which sought to assess the technical, economic and environmental feasibility of this technological change in rural contexts.

"Replacing internal combustion engines in agricultural systems not only reduces emissions, but improves the operational efficiency of irrigation and reduces overall energy consumption" [32]

Main contributions

The study brings three key contributions to the field of engineering:

- A comprehensive proposal for agricultural electrification, which includes technical design, economic evaluation and environmental impact analysis.
- A practical validation of the replacement of polluting technologies with more sustainable solutions in a rural environment in Ecuador, which contributes to closing existing gaps in the literature on real cases in developing countries.
- The demonstration that this transition contributes directly to the fulfillment of the Sustainable Development Goals (SDGs), especially SDGs 7 (clean energy) and 13 (climate action).

Practical and theoretical implications

From a practical point of view, the results can be replicated by other agricultural associations in the country, providing efficient and sustainable solutions for irrigation. They can also serve as an input for rural electrification programs, subsidies, or state incentives.

Life cycle analysis revealed that solar home systems generate up to 85% fewer greenhouse gas emissions than diesel generators.[33]

On the theoretical level, the study strengthens the conceptual framework on eco-efficiency and energy transition in agriculture, providing empirical evidence that can serve as a basis for future research on the design of sustainable agricultural systems, life cycle analysis or integration of renewable energies.

Recommendations for future studies

To enrich and expand this field of research, it is suggested:

- Replicate the study in other regions of the country, with different types of crops and geographical conditions, to validate its general applicability.
- Incorporate a social and cultural analysis, evaluating the perception of producers in the face of new technologies.
- To analyse the feasibility of integrating photovoltaic solar energy as an alternative source for the irrigation system.
- Carry out longitudinal studies that measure the economic and environmental performance of these systems in the medium and long term.

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7.- References.

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