Material Circularity Index (MCI) Assessment of Distributed Generation Technologies for Mexico's Energy Transition

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***Abstract*— This study evaluates the circularity performance of nine distributed generation (DG) technologies in Mexico using a streamlined Material Circularity Index (MCI) framework. The analysis integrates Life Cycle Inventory (LCI) data to quantify material flows during construction and End-of-Life stages, with a specific focus on the recovery potential (α) of critical materials, including steel, copper, and silicon. The results reveal significant disparities across technologies. Biogas and hydroelectric systems exhibit the highest circularity scores (0.36), reflecting favorable material recovery profiles, whereas wind (0.15) and solar photovoltaic systems (0.30) are constrained by the presence of composite materials and electronic waste, which limit recyclability. These findings underscore the dominant role of End-of-Life infrastructure in shaping circularity outcomes within emerging energy systems. The study demonstrates that material recovery potential is a critical determinant of circular performance in the Mexican DG context and identifies key technological and systemic barriers to circularity. By providing a comparative, data-driven assessment, this work offers policy-relevant insights to support the transition toward a more resource-efficient and circular distributed energy sector.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/10230

***Index Terms*— Material Circularity Index (MCI); life cycle inventory (LCI); material flow analysis; resource recovery; End-of-Life management; circular economy; renewable energy systems; energy transition.**

I. Introduction

THE rapid adoption of Distributed Generation (DG) in Mexico, particularly through renewable technologies such as solar photovoltaic and wind systems, is reshaping the national electricity sector [1]. Defined as generation or storage systems located near load centers, DG offers key advantages, including reduced transmission losses, increased integration of clean energy, and improved access in marginalized areas [2]. However, as installed capacity surpassed 3,300 MW by the end of 2023, according to the Energy Regulatory Commission (CRE), assessments have primarily focused on energy and economic performance, with limited attention to material sustainability. This gap highlights the need to evaluate DG systems through a Circular Economy (CE) perspective, which seeks to close material loops and minimize life cycle impacts [3], as illustrated in Fig. 1.

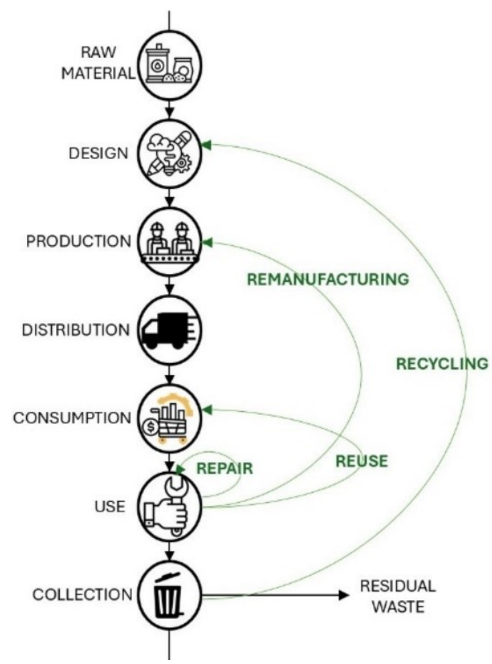

Fig. 1. Structure of CE.

In this context, assessing the extent to which DG systems incorporate principles of resource efficiency and material circularity requires robust and quantitative metrics. The Material Circularity Index (MCI) has emerged as a widely recognized index, providing a normalized measure (0-1) of a system's ability to retain materials within closed loops [4]. Unlike conventional metrics focused solely on greenhouse gas emissions or economic costs, the MCI explicitly captures the reduction of virgin resource consumption and the potential for material recovery [5]. Mexico's DG landscape is currently dominated by solar PV, representing over 99% of contracts. However, the National Electricity System Development

The associate editor coordinating the review of this manuscript and approving it for publication was Ricardo Arias (*Corresponding author: Rafael Peña Gallardo*).
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Program (PRODESEN) highlights the strategic potential of emerging technologies such as small-scale wind and biogas. In parallel, the continued use of hybrid and backup systems, including diesel, gas, and small-scale hydroelectric generation, underscores the need for a comprehensive evaluation of the energy system from a material perspective.

Despite growing interest in energy sustainability, the state of the art reveals key limitations in the application of circularity metrics to distributed energy systems. Most existing studies either focus on utility-scale technologies or rely on qualitative approaches, limiting their applicability to diverse and decentralized DG portfolios. Furthermore, there is a lack of harmonized, quantitative methodologies capable of consistently comparing circularity performance across multiple technologies, particularly under the data and infrastructure constraints typical of emerging economies.

This paper addresses these limitations by providing a systematic and comparative assessment of circularity across nine distributed generation (DG) technologies in Mexico. Building on the Material Circularity Index (MCI) framework, the study adopts a context-sensitive approach that emphasizes material recovery potential (α) as the primary determinant of circular performance. The novelty of this work lies in the integration of harmonized Life Cycle Inventory (LCI) data to evaluate material flows across construction and End-of-Life (EoL) stages, enabling a consistent cross-technology comparison within a unified analytical framework.

The main objective is to quantify and rank the circularity performance of DG technologies, identifying critical material bottlenecks and EoL constraints. In doing so, the study provides a robust, data-driven basis to inform policy design, technology selection, and strategic planning, supporting the transition toward a more resource-efficient and circular energy system in Mexico.

II. Literature Review

Recent global assessments by [6] have highlighted that the clean energy transition is significantly more mineral-intensive than fossil-based systems. However, most of these studies focus on developed economies with advanced recycling infrastructure. This research fills a critical gap by applying a localized MCI framework to the Mexican energy sector, where industrial maturity and waste regulations differ significantly from those in the Global North.

The CE has emerged as a key model for moving toward sustainable production systems, prioritizing resource regeneration, waste reduction, and optimizing the value of materials throughout their life cycle [7], although its quantitative application remains limited in energy systems. However, its effective implementation requires quantitative tools to measure the level of circularity of processes, products, and systems. In this context, circularity indicators have been established as fundamental tools for assessing the environmental, economic, and social performance of circular strategies, in addition to guiding policy and decision-making [8].

Early attempts to measure circularity focused on material efficiency indicators, such as recycling rates and recycled content percentages [9]. However, the complexity of current production systems has led to the development of more holistic indicators. The Materials Circularity Index (MCI), proposed by the Ellen MacArthur Foundation, set a precedent by including factors such as the origin of materials (virgin vs. recycled), product durability, and end-use, providing a score between 0 (linear) and 1 (circular) [10]. Similarly, methods such as the Circular Economy Index (CEI) and the Circular Potential Index (CPI) integrated additional dimensions, such as modular design, reverse logistics, and servitization-based business models [11].

At the macroeconomic level, institutions such as ECLAC have proposed indicators to assess progress in priority value chains, considering not only waste management but also energy efficiency and the incorporation of byproducts into new production processes [12]. At the business level, tools such as the Republic Services Circular Maturity Index have facilitated the assessment of organizations' circular maturity through three sub-indices: institutional commitment, operational execution, and material recovery [13].

The use of these indices has revealed critical patterns. For example, in the energy sector, recent research highlights that technologies such as solar and wind energy face specific challenges in circularity, especially in the management of composite materials and the recovery of critical metals [14]. Although the MCI has been widely used to evaluate individual products, its adaptation to complex systems (such as distributed generation plants) requires methodological modifications to include factors such as water resource efficiency and the incorporation of renewable energy into the supply chain [15].

One of the main challenges is the lack of standardization of indicators. As noted by [16], many indices prioritize environmental aspects, neglecting fundamental social and economic aspects, such as job creation or equitable access to circular technologies. Furthermore, most existing indicators were created in European or North American settings, limiting their applicability in regions such as Latin America, where inequalities in recycling infrastructure and circular economy policies persist.

Recent studies indicate a shift toward hybrid indices that combine both qualitative and quantitative analyses. One example is the Circular Energy Sustainability Index (CESI) [17], which integrates three dimensions: material selection, resource efficiency, and waste management, allowing for a holistic assessment of energy technologies. There is increasing interest in indicators that assess the likelihood of circularity. This refers to the capacity of systems to maintain materials within closed loops under realistic market and regulatory conditions.

III. Materials and Methods

A. *Conceptual Framework of Material Circularity*

The transition toward a CE in the energy sector requires a shift from linear take-make-dispose processes to regenerative systems where materials are conserved in closed cycles [17]. Unlike traditional environmental assessments that focus on emissions, this study adopts a technical cycle approach, focusing on materials such as metals and polymers that can be recovered and reincorporated into the industrial sector [18]. The conceptual basis for this evaluation is resource efficiency, aiming to decouple economic growth in the energy sector from the continuous extraction of virgin raw materials [19].

B. Material Circularity Index (MCI) Formulation

The primary analytical tool used in this research is the Material Circularity Index (MCI), originally developed by the Ellen MacArthur Foundation to assess material flows at the product level [4]. The MCI evaluates three key metrics: recycled content, linear flow, and recovery potential [20].

In its complete form, the MCI is defined by the interaction of two main components: the material recirculation (α) and the energy required for recovery (β). According to [21], the general formulation is expressed as:

$$MCI = \alpha \times \beta \tag{1}$$

where:

- α (Material Recirculation): Quantifies the relationship between the input and output mass of the material, representing the probability of recycling (Eq. 2).
- β (Energy Component): Accounts for the energy intensity required to produce and recover the materials (Eq. 3).

$$\alpha = \frac{Material\ recovered\ at\ the\ end\ of\ its\ useful\ life}{Total\ material\ demand} \tag{2}$$

$$\beta = \frac{Energy\ required\ for\ material\ recovery}{Energy\ required\ for\ primary\ production} \tag{3}$$

In this study, a strategic methodological assumption is made by setting β = 0 for all analyzed technologies. This decision is not merely due to data limitations. It reflects a methodological alignment with the specific context of the Mexican energy sector. While the country possesses a highly mature and integrated secondary market for metal recycling (α parameter), particularly for steel, copper, and aluminum, the specialized infrastructure and regulatory frameworks required for the high-level refurbishment or reuse of power components (β parameter), such as photovoltaic cells or composite wind blades, are currently in an embryonic stage or technically non-existent. Consequently, the circularity index is intentionally focused on the material recycling potential, as this represents a viable pathway for resource recovery in the local energy transition.

To ensure conceptual rigor, a clear distinction is maintained between recyclable and reusable materials. Recyclable materials (α) are those integrated into existing metallurgical and industrial value chains as secondary raw materials. In contrast, reusable materials refer to components that retain their structural and functional integrity for redeployment. By prioritizing the α parameter, this assessment shifts from a generic theoretical model to a regionally validated diagnostic tool, highlighting that while Mexico's metallic circularity is robust, a technological circularity gap remains due to the absence of advanced remanufacturing capabilities.

C. Methodological Rationale for Simplified Calculation

The MCI scale ranges from 0 (completely linear system using 100% virgin materials with no EoL recovery) to 1 (fully circular system with 100% recyclable or renewable materials) [22].

For this study, the methodology was simplified to focus exclusively on the α quotient. This decision is justified by two main factors:

- Material sensitivity: In the context of Mexico's DG, the physical management of waste (e.g., solar glass, turbine blades, and metals) constitutes a relevant technical and regulatory challenge.
- Data reliability: Due to the high complexity and lack of standardized data regarding the specific energy required to recover every individual material in the Mexican industrial landscape, the α parameter provides a more robust and replicable quantitative measure of the percentage probability of recycling for each technology.

Consequently, the circularity assessment in this paper is defined by the mass balance between the materials required for the construction of the generating technologies and the materials technically recoverable at the end of their useful life.

D. Case Studies and Data Inventory

To evaluate the circularity of DG in Mexico, nine diverse power generation technologies were selected based on their current and projected penetration in the national energy mix. The material inventory for each technology was compiled through a systematic review of specialized literature and Life Cycle Assessment (LCA) reports.

a) Data Sources and Technical Inventory

The Life Cycle Inventory (LCI) for each generating plant was corroborated using the technical parameters established in [23]. The following list summarizes the primary sources used to determine the mass of materials for both the construction and decommissioning phases.

- Photovoltaic [24].
- Biogas [25].
- Biomass [26].
- Cogeneration [27].
- Wind [28].
- Gas [29].
- Fuel oil [30].
- Diesel [31].
- Hydroelectric [28].

To ensure a rigorous comparison between the nine technologies, all LCI data were normalized to a functional unit of 1 kW of installed capacity. This normalization accounts for the different scales of the analyzed plants. Furthermore, the system boundaries were strictly defined as cradle-to-grave, encompassing raw material extraction, manufacturing, and EoL disposal. To address the heterogeneity of the sources, the data were filtered to include only those providing mass-based inventories of structural materials (steel, copper, concrete, etc.), to ensure methodological consistency across different years and geographic contexts.

b) Analytical Procedure for Material Flows

The determination of the recirculation quotient (α) follows a standardized mass balance. For each technology, every material component identified in the inventory (e.g., glass, steel, silicon, copper) is analyzed by comparing its total demand during the construction phase (M_{in}) against its recoverable mass at the end of its useful life (M_{out}).

For instance, the calculation considers the specific mass of materials such as glass in photovoltaic panels, where the difference between input mass and the technically recoverable fraction at the EoL stage defines the individual probability of recovery. This procedure is systematically applied to every material constituent of the nine technologies studied to derive a weighted circularity index at the plant level.

c) Product-Level Circularity Classification

Following the methodology illustrated in Fig. 2, the circularity assessment is categorized into material and functional characteristics. The material properties are evaluated based on two stages of the lifecycle:

1. Production Stage: Quantifies the proportion of reused materials without modification and the fraction of materials sourced from recycled or renewable origins.
2. EoL Stage: Determines the percentage of components that can be reintegrated into the value chain versus those destined for final disposal (linear flow).

E. Uncertainty and Limitations

The results of this study are subject to uncertainties associated with the use of secondary data sources and methodological assumptions. Variability in the underlying inventories, including differences in data sources, temporal scope, and system boundaries, may influence the comparability of material flows across technologies. Although efforts were made to harmonize the data through a consistent functional unit (1 kW) and a unified cradle-to-grave system boundary, residual inconsistencies may persist. In addition, the assumption of $\beta \approx 0$ and the focus on mass-based recovery (α) may introduce bias in technologies where energy recovery or component reuse could be significant. These limitations should be considered when interpreting the results, and future work should aim to incorporate primary data and expanded circularity metrics to improve accuracy and robustness.

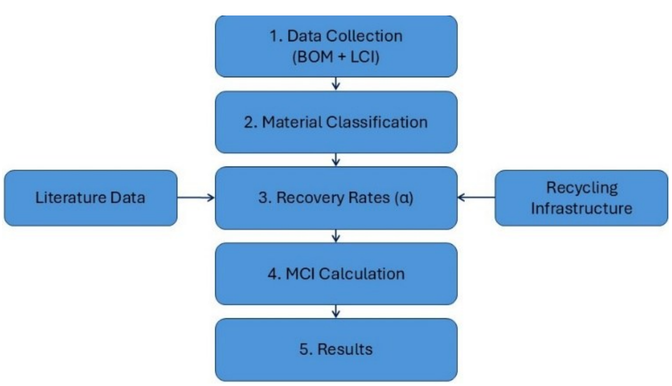

Fig. 2. Methodology to obtain the product-level circularity index.

IV. Results and Discussion

Tables I and II present data obtained through a LCA inventory harmonization process. Bills of Materials (BOMs) representing each distributed generation technology were used to quantify material and component inputs, based on reliable and widely recognized databases.

For the Dismantling and Circularity Index (ICM), recovery rates were determined through a systematic review of current industrial recycling practices, as well as the existing technological capacity for waste processing within a circular economy framework. In cases where the ICM is reported as a fixed value, full recovery of the base material is assumed for simplification.

The material recovery assessment, summarized in Table I, demonstrates significant variability in circularity potential across technologies. Metals such as steel, iron, and aluminum consistently show a near-complete circularity potential due to Mexico's well-established scrap metal markets and the high metallurgical purity of structural components.

TABLE I
Material Inventory and Recovery Potential for Distributed Generation Technologies in Mexico

Technology	Material category	Components	Recirculation Probability (α)
Photovoltaic	Metals	Aluminum frames, and Copper wiring	98.5% - 99.8%
	Glass	Front protective cover	75.6%
	Semiconductors	Silicon cells (purified)	93.7%
	Polymers	PET and Paper packaging	88.5% - 97.0%
Wind & Hydro	Ferrous Metals	Steel tower, Cast iron nacelle, and Turbine casing	100%
	Non-ferrous	Copper windings and Aluminum heat sinks	80.2% - 100%
	Electronics	Control units, and Power converters	100%
Bioenergy (Biogas/Biomass)	Structural Metals	Galvanized steel, Boiler iron, and Boilers	100%
	High-Density Polymers	HDPE pipes, and Polyethylene liners	100%
	Technical Fluids	Reusable Sodium hydroxide and Lubricants	100%
Fossil-based (Diesel/Gas/Fuel Oil)	Structural	Reinforced Concrete and Steel chassis	12.9% - 100%
	Alloys	42CrMo4 and AlCuMg2 (Engine components)	100%
	Polymers	Polypropylene, Polystyrene, and PVC pipe	100%

In contrast, critical materials like silicon in PV panels (93.7%) and copper in wind turbines (80.2%) present technical bottlenecks. While silicon has a high theoretical recovery rate, the energy-intensive process required to achieve solar-grade purity remains a significant economic barrier in the Mexican industrial context [24]. Similarly, the lower recovery rate of copper in some inventories reflects the complexity of separating it from contaminated insulation or resins.

Table II identifies the linear components, materials with 0% circularity, which represent the primary environmental liabilities of the Mexican DG sector. A critical finding is the presence of waste reinforced concrete and composite waste (plastic/polypropylene) in wind and hydroelectric infrastructures. Unlike metals, these materials often undergo downcycling (e.g., as road filler) rather than true circular reintegration, which aligns with the literature regarding the challenges of composite materials in energy transitions [21].

TABLE II
CHARACTERIZATION OF LINEAR FLOWS AND NON-RECIRCULATING WASTE STREAMS BY TECHNOLOGY

Technology	Residual Category	Specific Non-Reusable Materials (0% Circularity)
Photovoltaic & Wind	Industrial Scrap	Tin sheet and Steel
	Polymeric Waste	Plastic, Polyethylene, and Polypropylene
	Electronic Waste	Electric wiring and electronic equipment
	Inert Waste	Municipal solid waste, and reinforced concrete
Hydroelectric	Construction	Concrete and Transport-related emissions
Fossil-based	Operational Waste	Natural gas (consumed), Methane, and Carbon dioxide
(Diesel, Gas, Oil)	Structural Scrap	High-High-alloy steel, Cast-iron, and Plastic components

The final MCI results (Table III) reveal that Biogas and Hydroelectric technologies are the leaders in circularity in Mexico, both reaching 36%. This performance is attributed to the high proportion of standardized metallic components and the potential for organic byproduct valorization, consistent with biological cycle principles of the circular economy [17].

TABLE III
PERCENTAGE OF CIRCULARITY OF DISTRIBUTED GENERATION PLANTS

Technology	Circularity
Photovoltaic	30%
Biogas	36%
Biomass	3%
Cogeneration	0%
Wind	15%
Gas	16%
Fuel oil	33%
Diesel	33%
Hydroelectric	36%

For better understanding, Table III can be represented as a bar chart to make the circularity percentage clearer, as shown in Fig. 3. The disparity observed in Fig. 3 is directly correlated with the material intensities detailed in Table I. For instance, the high MCI score for Biogas (36%) is explained by the near-complete recirculation potential of galvanized steel and HDPE pipes, which represent over 80% of its total mass. Conversely, the low performance of Wind energy (15%) in the graph stems from the 0% circularity of composite blades identified in Table II.

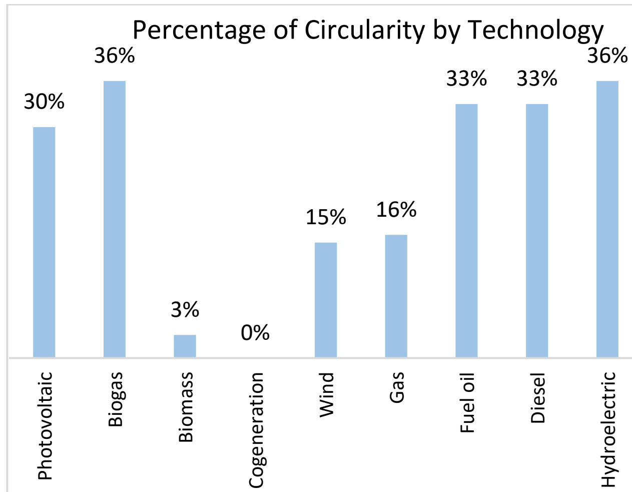

Fig. 3. Percentage of circularity by type of technology.

When comparing the MCI results (Table III) with material intensities, a key finding is that the main technologies driving Mexico's energy transition, such as solar photovoltaics (30%) and wind power (15%), exhibit a significant circularity gap. Despite their superiority in terms of operational emissions, these technologies introduce a circularity gap in the national electricity system.

In the case of wind energy, this circularity gap is embodied in the wind turbine blades. Composed of epoxy resins and reinforced fiberglass, these structures currently lack technical or economic valorization pathways within Mexico, resulting in their final disposal in landfills or their degradation through downcycling. This confinement of complex materials represents an environmental challenge that may conflict with the principles of a holistic energy transition.

Similarly, photovoltaic technology faces a circularity gap due to its layered module architecture. Although the aluminum frame is highly circular, the ethylene-vinyl acetate (EVA) encapsulants and back sheets function as a physical barrier that limits the recovery of high-purity silicon. This multilayer configuration limits material recovery that, given the imminent wave of photovoltaic waste in Mexico, highlights the need for a transition to eco-design to avoid the saturation of final disposal sites.

A paradoxical result is that diesel and fuel oil plants (33%) surpass wind energy in circularity. These results should be interpreted within the limitations of the simplified MCI formulation, particularly when comparing technologies with different energy recovery or reuse potentials. This result reflects the structural characteristics of the MCI and is a consequence of the metallurgical simplicity of fossil-based systems. Composed entirely of ferrous and copper alloys with mature recycling markets in Mexico, these systems achieve a near-perfect mass cycle closure.

Our findings regarding the circularity gap of wind blades and PV laminates align with the concerns raised in [32], which argue that, without a shift toward design for disassembly, waste from renewable infrastructure could undermine its decarbonization benefits.

However, it is important to distinguish between Material Circularity and global sustainability. A high MCI score for a diesel plant indicates efficient management of its physical structure at the end of its useful life, but it does not compensate for its thermodynamic linearity or its greenhouse gas emissions. Therefore, these results highlight the need for improvements in renewable energy systems to close their material recovery constraint. The objective is for clean infrastructure to reach the recoverability levels of the traditional mechanical industry, reducing these circularity gaps that may compromise long-term environmental performance.

The results demonstrate that the transition in Mexico is currently restricted by technical and infrastructure factors that prioritize energy output over resource efficiency. The low scores for biomass (3%) and cogeneration (0%) reinforce the existence of a linear system behavior where thermal byproducts and biological nutrients are not reintegrated into the production cycle.

For the transition to be truly circular, public policy frameworks should incentivize not only decarbonization but also the reduction of circularity gaps by supporting the development of secondary markets for non-metallic components. Addressing these constraints will help ensure that emerging distributed generation infrastructure does not create long-term environmental burdens.

The findings of this study have important implications for energy and circular economy policy in Mexico. They highlight the need to complement current decarbonization strategies with material-focused approaches that address end-of-life management and resource recovery. The identification of circularity bottlenecks—such as limited recycling infrastructure for composite materials in wind systems and polymers in photovoltaic technologies—indicates that targeted investments in recycling technologies and reverse logistics systems are required. Furthermore, policy frameworks could incorporate incentives for material recovery and design-for-circularity in emerging energy technologies, helping to ensure that the expansion of renewable energy systems does not lead to new forms of material inefficiency. By integrating circularity criteria into energy planning and technology selection, policymakers can support a more resource-efficient and resilient energy transition.

V. Conclusion

This study presents a quantitative assessment of the material circularity of nine distributed generation (DG) technologies in Mexico using a streamlined Material Circularity Index (MCI) approach. The results reveal significant variability in circular performance, primarily driven by material composition and recyclability.

Biogas and small-scale hydroelectric systems exhibit the highest circularity levels (approximately 36%), reflecting favorable material recovery potential. In contrast, wind (15%) and solar PV (30%) show lower performance due to the presence of composite materials and limited recycling infrastructure. Biomass and cogeneration technologies present the lowest circularity levels, highlighting critical gaps in the management of organic and thermal byproducts.

A key finding of this study is that renewability does not necessarily imply circularity. Technologies with simpler and more recyclable material structures, including certain fossil-based systems, may outperform more complex renewable technologies in terms of material recirculation.

Overall, this work provides a quantitative baseline for assessing circularity in Mexico's DG sector and identifies priority areas for improving material recovery. These findings offer relevant insights for policymakers and energy planners aiming to support a more resource-efficient and truly sustainable energy transition.

Acknowledgments

The authors would like to acknowledge the Universidad Autónoma de San Luis Potosí through the Facultad de Ingeniería for the facilities provided for this research. Diana Laura Ovalle Flores thanks the financial support received from SECIHTI through a scholarship to conduct her PhD studies.

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