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Clean development mechanisms in Latin America: Efficiency analysis of energy-generating projects

Antonio Carlos Pacagnella Junior[1] | Gustavo Hermínio Salati Marcondes de Moraes[2] | Adauto Lucas da Silva[2] | Fernando Ferrari Putti[3] | Wagner Wilson Bortoletto[2]

[1]Escola de Engenharia de São Carlos, Universidade de São Paulo, São Paulo, Brazil

[2]Faculdade de Ciências Aplicadas, Universidade Estadual de Campinas, UNICAMP, Campinas, Brazil

[3]Faculdade de Ciências e Engenharia, Universidade Estadual Julio de Mesquita Filho, UNESP, São Paulo, Brazil

Correspondence
Antonio Carlos Pacagnella Junior, Escola de Engenharia de São Carlos, Universidade de São Paulo, USP, São Paulo, Brazil.
Email: acpjr@usp.br

Abstract

This research addresses two key questions related to Clean Development Mechanism (CDM) This research aimed to address two research questions related to CDM projects focused on energy generation in Latin America. The first question aimed to identify the most efficient projects carried out in this region, while the second question sought to identify their characteristics. These questions were proposed based on a clear gap identified in the scientific literature, particularly regarding these ventures developed in the region, which may be of interest to researchers, investors, and project managers alike. To answer these questions, a quantitative analysis was conducted using the database on CDM projects provided by the United Nations Framework Convention on Climate Change, employing two techniques. The first technique used was Data Envelopment Analysis, which generated an efficiency ranking for these projects. In this study, efficiency is considered as the results achieved by the project in terms of energy generation capacity and carbon emission reduction, relative to the resources invested in it. The second technique was the non-parametric Mann–Whitney test, which helped identify characteristics that exhibited significant differences in efficiency. Among the findings, three key characteristics were identified as relevant in explaining this difference: project scale, type, and country where they were developed. Large-scale projects—specifically those in the categories of Methane Avoidance, Landfill Gas, and Energy Efficiency Supply Side—as well as projects carried out in Mexico and Colombia, demonstrated significantly higher efficiency based on the model used in this research. Furthermore, Hydro and Biomass Energy projects were identified as having significantly lower efficiency compared to the others. The outcomes of this study hold significance in two aspects. Firstly, from an academic standpoint, it expands the understanding of project characteristics of these projects in Latin America by establishing a comparative analysis among them. Secondly, from a more practical perspective, the results can guide investors in defining a more suitable profile for energy-generating CDM projects, thereby reducing risks and increasing the likelihood of success. Moreover, these findings can lay the foundation for the formulation of public policies aimed at promoting projects with a more efficient profile. This is especially important given the waning interest in this crucial mechanism over the past decade, potentially spurring the execution of new projects and altering this reality.

KEYWORDS
clean development mechanisms, DEA, efficiency, investment analysis, public policies

1 | INTRODUCTION

In recent decades, the growing concern with global warming has prompted government managers to seek alternatives that enable economic development while minimizing environmental impacts. These impacts include rising sea levels, extreme weather events, and habitat loss for wildlife. In response, government managers have explored a range of alternatives, such as renewable energy sources and energy efficiency measures. One major milestone in this effort was the creation of the Kyoto Protocol, a treaty that established targets for reducing greenhouse gas (GHG) emissions for developed countries.

The Kyoto Protocol was implemented on February 16, 2005. The treaty established a first commitment period from 2008 to 2012, during which participating countries were divided into Annex I and Annex II. Annex I parties undertook to reduce their GHG emissions by an average of 5% compared to 1990 levels. In the second commitment period, from 2013 to 2020, parties aimed to improve this reduction to 18% of the 1990 levels. Annex II parties were developed countries that provided financial and technological support to help Annex I countries achieve their GHG reduction targets.[1]

According to Bortoletto et al.,[2] the Kyoto Protocol established three flexible mechanisms to reduce compliance costs for industrialized countries while offering geographical and temporal flexibility. These mechanisms are International Emissions Trading, Joint Implementation, and the Clean Development Mechanism (CDM). Among them, the CDM is particularly notable for its flexibility, as it allows developed countries from "Annex I" to invest in projects in developing countries from "non-Annex I" and receive credits for certified emission reductions (CERs), equivalent to one metric tonne of CO_2e reduced, once approved.[3]

According to Pacagnella Junior et al.,[4] there are several types of CDM projects, such as Renewed Resource-Based (Hydro, Solar, Wind, etc.), Fossil Fuel (switch, transport), Afforestation/Deforestation, Methane Avoidance, and others. The primary objective of these projects is to reduce Greenhouse Gas (GHG) emissions, but some of them can also generate energy, which can be considered an additional advantage of CDMs.

As observed by Watts et al.,[5] although CDM projects have been carried out in various countries and regions of "Annex II," Latin America stands out for being an active participant and the first region where all eligible countries have hosted a CDM project. Additionally, the authors highlight that, of the global CDM project portfolio, which includes a total of 4326 projects, 668 were implemented in Latin America, representing 15.44%. This makes the continent the second with the highest number of CDMs, following only the Asia-Pacific region.

Rising population and economic development are expected to drive a significant increase in global energy demand in the coming decades. Specifically, in Latin America, the International Energy Agency (IEA)[6] predicts that global energy demand will rise by approximately 60% by 2040, This poses a significant challenge to the region's energy supply, as traditional fossil fuels are becoming scarcer and their use has a negative impact on the environment. Thus, meeting the growing energy demands sustainably will require significant investment and innovation in more efficient energy technologies.

In addition, Camioto et al.[7] suggest that Latin America has demonstrated significant economic growth and plays a crucial role in the global economy. Nevertheless, the increase in energy consumption poses a serious challenge in the contemporary world, and implementing policies to ensure energy efficiency has become a priority for nations seeking to advance their economies.

Higher levels of economic activity typically correspond to higher levels of energy consumption and associated environmental impacts. Therefore, improving energy efficiency can offer additional security and benefits, including reduced CO_2 emissions and decreased reliance on energy imports.[8]

In this sense, Benites-Lazaro et al.[9] argues that the region's economy is heavily reliant on resource extraction, which consumes significant amounts of energy. This dependence has fostered greater specialization in the export of primary commodities, contributing to increased carbon emissions, deforestation, biodiversity loss, land-use changes, and the degradation of ecosystem services. Thus, CDM energy-generating projects can help Latin America by promoting the transition to cleaner and more sustainable energy sources, reducing greenhouse gas emissions.

Additionally, as noted by Ottonelli et al.,[10] CDM projects play a crucial role in promoting diversification in electricity generation across many Latin American countries. These projects can also drive local economic development, create green jobs, enhance energy security, and support the region in fulfilling its climate commitments.

Another important argument is that in developing countries, as population density increases and industrialization accelerates, the demand for energy continues to grow, both in terms of production and consumption. During the early stages of development, countries often prioritize industrial production and job creation, with environmental concerns taking a backseat. However, as environmental regulations become stricter, there is an increasing need for incentives to promote the adoption of environmentally friendly energy sources in industrial processes. As a result, the demand for sustainable energy resources is expected to rise, driven by growing environmental awareness in these regions, which is anticipated to surpass that of developed countries.[11]

In this discussion, it is important to highlight that CDM projects require significant investments, with expectations of both financial and environmental returns (particularly in terms of reducing GHG emissions). Therefore, given the large portfolio of energy-generating CDM types that can be implemented, it is crucial to consider the efficiency of these ventures.

In this regard, Pacagnella Junior et al.[4] emphasize that efficiency is a measure that considers the generation of outputs relative to resource consumption. In the case of an energy-generating CDM project, this should include elements such as the resources invested in the project and its outcomes in terms of energy generation capacity and carbon emission reduction.

Similarly, Zhang et al.[12] indicate that it is greatly significant to investigate efficiency in terms of financial return and carbon emission reduction performance in CDM projects, highlighting that the literature remains controversial on the subject.

Based on the preceding arguments, two critical research questions arise: First, which energy-generating CDM projects can be considered efficient in a Latin American context? Secondly, what are the characteristics that differentiate the most efficient projects from the least efficient ones?

These questions were proposed based on an assessment of the existing literature, which offers limited exploration of this topic in Latin America. Thus, the research findings can push the boundaries of knowledge by enhancing the understanding of energy-generating CDM projects that have yielded the most significant results in relation to the resources invested. Moreover, by identifying the differences between the most and least efficient projects, the study enables the recognition and comprehension of potential factors that support investment decisions related to these ventures—something that the scientific literature has not yet presented in a consolidated manner.

To address these questions, this study proposes a two-step methodology using, first, a Data Envelopment Analysis (DEA) applied to energy-generating CDM projects implemented in Latin America to assess their technical efficiency and second, statistical tests in order to identify the characteristics that differentiate the more efficient projects.

According to Choi et al.,[13] investments in low-carbon technology is often fraught with uncertainty, and as a result, it may not be affordable for many developing countries. These Technologies, according to Chen et al.,[14] are mainly renewable energy technologies with zero or lower emissions, but also include carbon reduction technologies for energy efficiency and carbon capture and storage.

Against this backdrop, one potential solution to the carbon emission issue could be to share green growth by leveraging each other's technologies and experiences. Thus, the findings from this study can provide valuable information as a benchmark to investors and public managers, which can be used to promote the implementation of more efficient energy-generating CDM projects in the region.

The rest of this paper is structured as follows: Section 2 provides the theoretical background for the research, and Section 3 outlines the methodological framework used in the study. In Section 4, we describe and analyze the results obtained with the DEA technique and statistical analysis. Lastly, Section 5 presents the conclusions of the study, discusses the limitations of the research, and provides suggestions for future research.

2 | ENERGY-GENERATING CDMs IN LATIN AMERICA

Access to energy is a critical factor in supporting the economic and social development of countries, particularly in regions like Latin America where the majority of countries are still developing. In order to achieve sustainable growth and improve the quality of life for their citizens, these countries require efficient and reliable energy sources and services.[15]

In this sense, according to Rehermann and Pablo-Romero,[16] since the end of the last century, Latin America has experienced significant growth, which has coincided with a notable increase in energy demand. As a result, the region has become the fastest-growing in terms of energy consumption worldwide. This growth has largely been fueled by large investment inflows received by the region.

Energy is a fundamental factor in production, and economic growth demands intensive energy use. However, the increasing use of energy and associated greenhouse gas emissions have been identified as the primary cause of adverse environmental effects and climate change. Consequently, climate change and energy consumption have become two of the most complex global challenges facing human development.[17]

Montalbano and Nenci[18] argue that despite the availability of energy resources, including hydrocarbons, hydroelectricity, and biofuels, and the progress that some countries of Latin America have made recently in terms of using renewable energy sources, these economies continue to grapple with significant economic, social, and environmental challenges in the energy sector. Furthermore, there is a pressing need to double installed power capacity to meet the rising demand for electricity, and the outdated grid infrastructure necessitates substantial modernization and expansion efforts.

Since the late 20th century, growing concern over the environmental impacts of economic development has pressured governments worldwide to adopt policies that support sustainable development. In this context, Selvakkumaran et al.[19] note that the Kyoto Protocol—introduced by the United Nations in 1997—aims to promote environmentally sustainable policies that align with economic growth.

Among the mechanisms established by the Kyoto Protocol, the CDM has been the most widely adopted. Latin America ranks second globally, after Asia, in the number of implemented CDM projects. According to the UNFCCC, over 1000 projects have been registered in the region since 2004, with approximately 65% focused on energy generation.

Figure 1 illustrates the trends in energy-generating CDM projects registered in Latin America from 2004 to 2020. The data indicates an upward trend until 2012, with 247 out of 638 (38.71%) projects registered in that year, which marked the end of the first commitment period. Subsequently, there was a downward trend until the registration of the last energy-generating project in 2020. Based on data

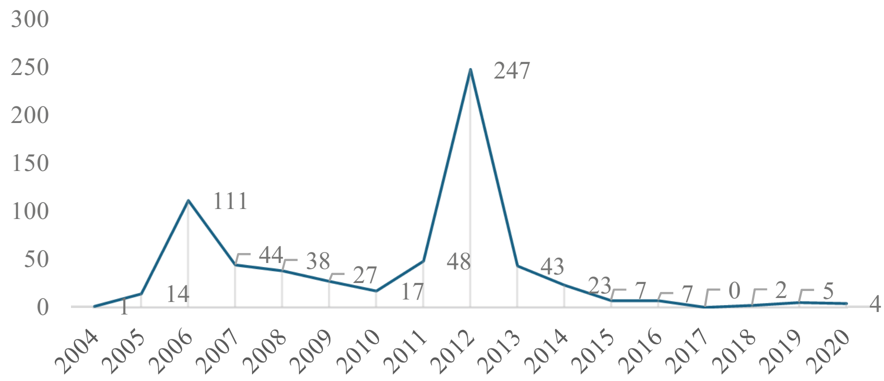

FIGURE 1 Timeline of energy generating projects registered in Latin America.

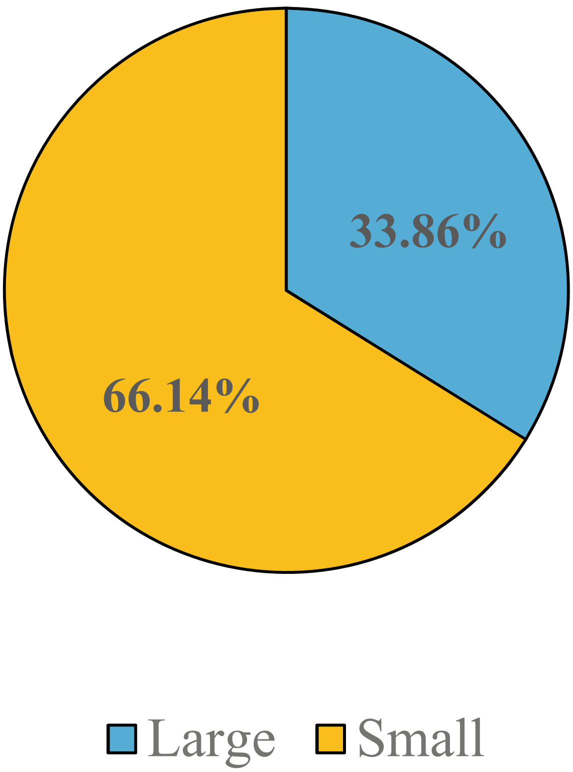

FIGURE 2 Energy generating Clean Development Mechanism projects scale classification.

extracted from the UNFCCC database, it has been observed that a total of 638 energy-generating projects have been formally recorded in various Latin American countries since the year 2004. Collectively, these undertakings have contributed to a substantial installed capacity of 36,360.94 MW, encompassing both thermal and electric power generation. The main features of these projects are presented below.

Figure 2 shows that the bulk of these projects are labeled as "small" (representing 422 projects, which accounts for 33.86% of the total). This is a key feature of Latin America's energy-generating CDM project portfolio. According to the UNFCCC,[20] large-scale methodologies can be applied to projects of any size, whereas small-scale methodologies are limited to projects that meet specific size criteria and are categorized into three types:

- Type I: Renewable energy project activities with a maximum production capacity of 15 megawatts (or an appropriate equivalent);
- Type II: Energy efficiency improvement project activities that reduce energy consumption on the supply and/or demand side, with a maximum production (i.e., maximum savings) of 60 gigawatt-hours per year (or an appropriate equivalent);
- Type III: Other project activities that result in emissions reductions equal to or less than 60 ktCO_2eq per year.

Given the conditions in Latin America, small-scale CDMs are often a more practical option, as they are less complex and require lower levels of investment to implement, making them more accessible than larger projects.

In addition, as can be seen in Figure 3, only 17.71% (or 113 projects) of these projects are designed to sell electricity as a form of additional revenue, indicating the preference in these projects for generating energy to meet local demands and not producing surplus that can be traded to increase the return on investment.

Another characteristic of CDM projects carried out in Latin American countries is their types, which are described in Figure 4.

As can be observed in Figure 4, the most common type of energy-generating CDM in Latin America is Hydro, which is widely used due to the region's potential for hydropower, as it is extensively traversed by rivers and represents 38.07% of the total. The second most frequent type is Wind, accounting for 21.96% of the projects in the region, following a global trend of such projects in the last decade. The region also has areas well-suited for the implementation of this type of CDM, such as the Brazilian northeastern coast. The third most utilized type is Biomass Energy, typically associated with the burning of agricultural residues, such as in the case of sugarcane, representing 11.13%. The remaining types are divided among Landfill gas, Methane avoidance, Solar, Geothermal, Energy efficiency supply side, Energy efficiency industry, Coal bed/Mine, and Fugitive projects.

As observed, the number of CDM projects in Latin America significantly decreased after 2012, following the global trend. Several factors can be cited as influencers of this phenomenon, such as uncertainty regarding the carbon credit market or economic crises that occurred worldwide or locally in many host countries. However, the importance of these projects for clean energy generation, making a significant contribution to the energy matrix of these countries, is undeniable since the region is second in the world in terms of number of energy-generating projects and issued CERs.

In addition, it is important to mention that the implementation of CDMs in Latin America is deeply shaped by the region's structural characteristics, particularly in terms of socioeconomic diversity and governance challenges. Although Latin American countries have played a significant role in the global carbon market, these initiatives often face limitations imposed by local contexts.

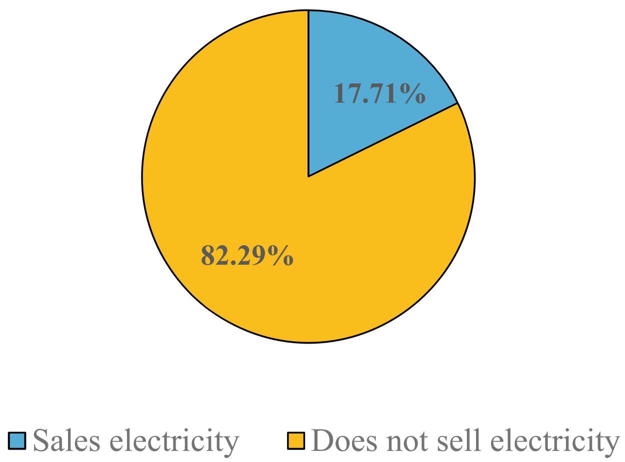

FIGURE 3 Additional revenue from electricity sale of energy-generating Clean Development Mechanism projects.

Environmental governance, for instance, represents one of the main obstacles to the effectiveness of CDMs. According to De la Mora-De la Mora,[21] the lack of a consolidated democratic tradition that recognizes society as a subject of rights undermines the relationship between the state and local communities. The fragility in upholding the rule of law has direct consequences for ecosystems and the long-term viability of sustainable projects. In countries with greater institutional stability, such as Brazil and Mexico, some progress has been made through public-private partnerships. However, in other nations across the region, the lack of political will, coupled with limited infrastructure and inadequate regulatory frameworks, hinders the successful implementation of CDM projects.

Moreover, Latin America's fiscal context presents additional challenges. As Jalles and Pessino[22] point out, many countries in the region face high levels of public debt, persistent fiscal deficits, and macroeconomic instability. Their heavy dependence on a few key sources of revenue—such as commodity exports—makes governments particularly vulnerable to external shocks, complicating the maintenance of stable fiscal policies. This financial instability limits the capacity of states to provide the institutional and economic support needed for clean development initiatives.

In this context, the pursuit of knowledge aimed at reducing uncertainty in investments made in the CDM projects assumes significant importance in generating information that can effectively support investment decisions and public policy-making. A study conducted by Watts et al.[5] on the portfolio of CDM projects in Latin America revealed a bias toward the implementation of low-cost projects, often overshadowing the imperative of sustainable development. Furthermore, Benites-Lazaro et al.[9] found that companies in the region have a limited perception of government incentives, indicating a pressing need for a more comprehensive understanding of the performance of existing projects.

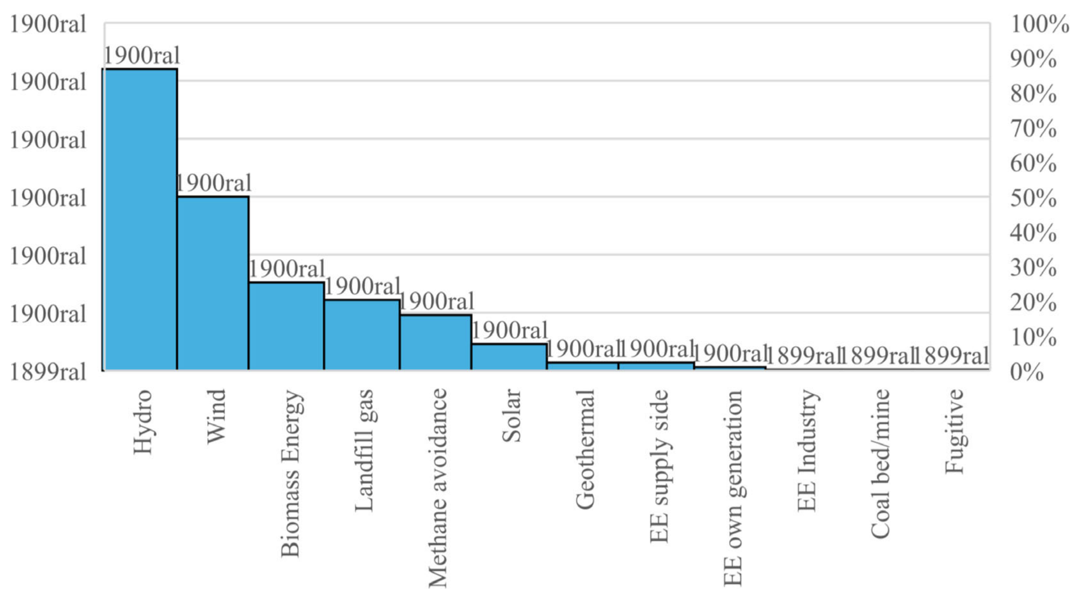

FIGURE 4 Types of energy-generating Clean Development Mechanism projects in Latin America.

Considering the relevance of CDM projects as a means to promote sustainable development, analyzing their performance is a common focus in the literature. In this regard, several authors have explored this path, such as Hacking[23], Shi et al.[24], Cansino et al.[25], and Singh.[26] However, studies focusing on Latin America are much rarer, with notable exceptions being Benites-Lazaro and Mello-Théry[27] and Ottonelli et al.[10]

Furthermore, in general, the studies analyze the performance of these projects from perspectives tied only to the outcomes achieved (such as emission reductions, increased green areas, financial returns, jobs created, and others), rather than taking a global approach that compares the different projects in the Latin American portfolio in terms of the benefits generated relative to the investment made.

This approach, which focuses on analyzing the relative and comparative efficiency of these projects, specifically in Latin America, has not been identified in the scientific literature, representing a gap to be explored. This justifies the proposal of the present study.

The results of this analysis should highlight the key characteristics of efficient CDM energy-generating projects, advance knowledge in this field, and assist investors in making informed managerial decisions. Additionally, it should help public administrators design effective incentives and attract investments to support these initiatives.

3 | MATERIALS AND METHODS

To answer the research questions outlined in the article, a two-step quantitative approach was employed, utilizing secondary data from the UNFCCC. The sample used consists of 190 energy-generating CDM projects conducted in Latin America from 2004 to 2020. Although the database used includes more projects, only these had complete information and could be analyzed in this study. The characteristics of these projects are presented in Section 4.

The first step of the research involved evaluating the efficiency of energy-generating CDM projects implemented in Latin America using the DEA technique. In the second phase, a non-parametric statistical test (Mann–Whitney) was applied to differentiate the most efficient CDM projects from the others. These techniques were used to address the research questions outlined in the introduction. The DEA technique identified the most efficient CDM projects in the sample, answering the first question, while the Mann–Whitney test helped determine which features significantly differ between the efficient projects and the others, thereby answering the second question.

Regarding the first step, as stated by Campisi et al.[28], DEA is a non-parametric optimization method that utilizes input and output data from a selected sample of decision-making units (DMUs), such as the CDM projects in this case, to construct a piece-wise linear surface known as a production frontier or envelopment. This frontier is determined by solving a sequence of linear programming problems, and the relative technical efficiency is measured by the distance between the frontier and the observed data point for the DMU's input or output.

Numerous studies utilizing DEA models have been published, and the technique has been extensively employed for efficiency analysis in various business scenarios and industrial sectors, thus becoming one of the most popular techniques for performance appraisal. Although unconventional in the literature, the approach utilized in this research to analyze the efficiency of the projects and utilize it as an indicator to aid investment is not novel. Examples of previous studies utilizing this approach include Bostian et al.,[29] Zeng et al.,[30] and Pacagnella Junior et al.[4] Figure 5 presents the proposed conceptual model to evaluate the efficiency of energy-generating CDM projects in Latin America.

Figure 5 shows a conceptual model that illustrates the input and output variables and characterizes each energy-generating CDM project as a Decision Making Unit (DMU), which, according to Martín-Gamboa and Iribarren,[31] can be defined as a homogeneous entity responsible for converting inputs into outputs. In the proposed model, the basic resources used by a CDM project are considered as inputs, which include financial investment (in US$) and duration in days. As for the outputs, the model considers that an energy-generating CDM project has the following main results: installed capacity (MW), total greenhouse gas reductions represented in CO2eq, and total Certified Emission Reductions (CERs).

To conduct the efficiency evaluation, we utilized a Variable Return of Scale (VRS) DEA model, commonly referred to as the BCC model, which was initially proposed by Barnes, Charnes, and Cooper in 1984. We employed an output-oriented approach for our analysis, as outlined by Chachuli in 2021.

The mathematical expression of the model is as follows:

$$\text{Min} = \sum_{J=1}^{n} v_j x_{j0} - w. \tag{1}$$

Subject to

$$\sum_{i=1}^{m} u_i \times y_{i0} = 1,$$

$$\sum_{i=1}^{m} u_i \times y_{ik} - \sum_{j=1}^{n} v_j \times x_{jk} + w \le 0 \text{ for } k = 1,2,\ldots h.$$

In this context, the variables can be defined as follows: x_{jk}: represents the amount of input j for DMU k. y_{ik} represents the amount of output i for DMU k. x_{j0} represents the amount of input j for the DMU under analysis. y_{i0} represents the amount of output i for the DMU under analysis. v_j represents the weight of input j for the DMU under analysis. u_i represents the weight of output i for the DMU under analysis. w represents the scale factor. m represents the number of outputs analyzed. n represents the number of inputs analyzed. h represents the number of DMUs analyzed.

In this process, an important aspect is the wights u_i and v_j, calculated through a linear programming process, with the goal of maximizing the efficiency of each decision-making unit (DMU), given the constraints imposed by the model. The weights assigned to the DMUs reflect the relative contribution of each DMU to the efficiency of the DMU under analysis. These weights can vary for each DMU, depending on its efficiency relationship with the other units.

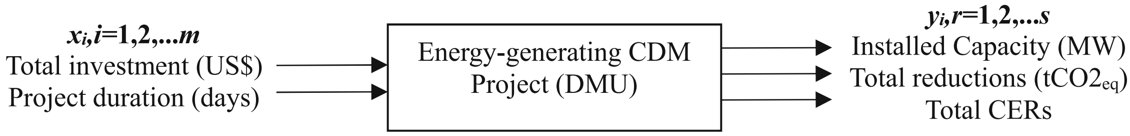

FIGURE 5 Data Envelopment Analysis model.

The sample data was analyzed using the PIM-DEA software, employing the mathematical model highlighted in Equation (1). The selection of the VRS model was motivated by the scale differences among the projects, which could potentially introduce distortions in the efficiency ranking. The choice of an output-oriented approach was made by the authors, who believe it is important to prioritize the outcomes of the Decision-Making Units (CDMs), specifically in terms of output generation (such as energy generation capacity, reduction of GHGs, and acquisition of CERs).

It is important to highlight that the robustness of the chosen methodology and the validity of the obtained results are checked using the bootstrapping method, considering 1000 interactions, following the procedure suggested by Cooper et al.[32]

In the subsequent phase of the research, a series of Mann–Whitney tests were conducted using SPSS v.23. These tests aimed to identify the project characteristics that show statistically significant differences between two groups sharing the same characteristic, such as scale (small or large), country, and project type (each compared to the total). This test, also known as Wilcoxon-Mann–Whitney or WMW test, is a non-parametric test that compares two independent samples from the same distribution to determine if the values in one sample are significantly greater than those in the other.[33]

As a non-parametric test, the WMW test does not require assumptions about the data. However, it should be used with continuous data, which is the case with the ranking generated by the DEA technique. The results of the tests revealed insights that can be used to better understand the characteristics that differentiate the more efficient projects from the others, and these results will be presented and discussed in the next section.

4 | RESULTS AND DISCUSSION

As described in the previous section, the sample used in this study consists of 190 energy-generating CDM projects. Although there are a total of 638 projects of this kind carried out in Latin America, only a portion of them in the UNFCCC database had the complete data necessary for the analysis conducted in this study.

Considering the sample size calculation for proportions in finite populations suggested by Verma and Verma[34], we verified that the sample is representative of the population when considering a 90% confidence level.

Table 1 presents a summary of the inputs and outputs used in the first stage of the research.

As observed in Table 1, in terms of invested capital, the projects in the sample demonstrate a wide variation, ranging from a small project of $500,000 to a mega-project of approximately $6.2 billion, with an average of approximately $146 million.

The project's credit period has an average of approximately 4000 days, with an average reduction of 288,000 tCO_2eq emissions and an average energy generation capacity of approximately 91 MW, having obtained an average of approximately 146 million CERs.

In researches that uses Data Envelopment Analysis as an analytical technique, it is common to present the efficiency ranking with all DMUs (Decision-Making Units). However, since the sample size is too large to be presented in this way, a histogram was constructed as a way to summarize the results, as shown in Figure 6.

Figure 6 shows that 60 CDM projects fall within the range of 0.01% to 10.00% efficiency, 38 projects fall between 10.01% and 20.00%, and 36 projects fall between 20.01% and 30.00%. These 134 projects are below the average efficiency of the sample, which is 32.39%. As positive highlights, there are 16 projects in the range of 90.00% to 100.00% efficiency, and among these, 14 are considered benchmarks (meaning they have 100.00% in the efficiency ranking). The benchmark projects are presented in Table 2.

As observed in Table 2, among the CDM projects considered benchmarks, there is a predominance of large-scale projects (only 2 out of 14 projects are small-scale). Furthermore, regarding the project type, the most frequent is "Landfill gas" (6 projects), followed by "Hydro" (4 projects), "Methane avoidance" (2 projects), and "EE supply side" and "Biomass energy" (1 project each). Additionally, it can be observed that the projects were conducted in 4 different countries, with a predominance in Mexico (5 projects) and Brazil (4), but also in Colombia, Guatemala, and Argentina (1 project each).

In summary, the following points can be highlighted from Figure 6 and Table 2:

- There are 16 projects in the highest efficiency stratum, of which 14 are considered benchmarks (100% efficiency);
- The vast majority of projects (134) fall below the sample's average efficiency, which is 32.39%;
- Regarding type, the most frequent among the benchmarks are landfill gas and methane avoidance projects;
- As for the countries where the benchmark projects were implemented, the most frequent are Brazil and Mexico;
- Most of the benchmark projects are large-scale.

It is important to highlight that the technique performs a comparative analysis between projects (DMUs) in terms of input consumption

TABLE 1 Summary of inputs and outputs of the model.

	Total capital investment (USD)	Total crediting period (days)	Total reductions (tCO_{2eq})	Installed capacity (MW elec/thermal)	Total CERs issued
Mean	146,401,867.28	4085,96	287,700,67	91,01	146,401,867.28
Std. Deviation	583,620,057.29	1568,47	878,646,45	379,98	583,620,057.29
Minimum	500,000.00	2555,00	1877,00	0,01	500,000.00
Maximun	6,255,708,160.00	7668,00	10,500,936,00	3750,00	6,255,708,160.00

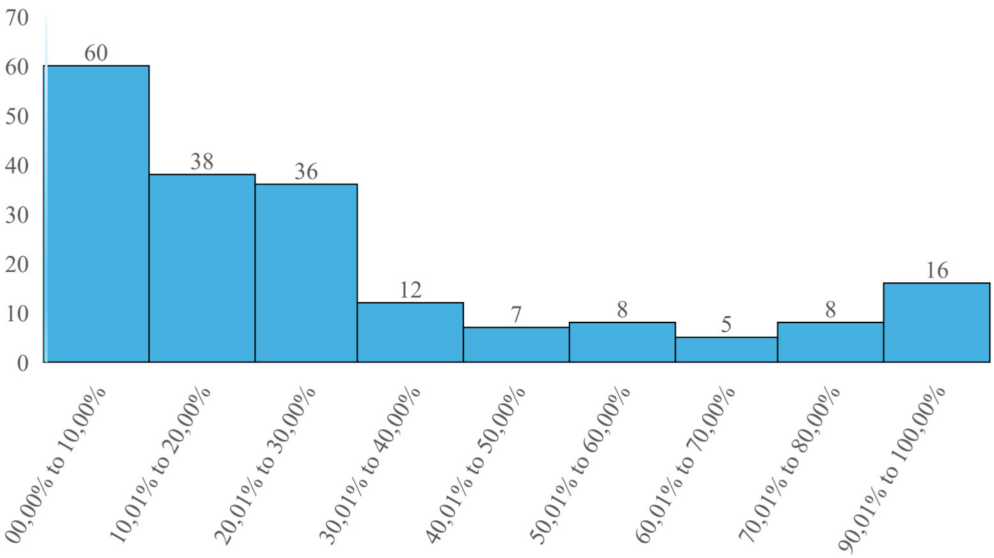

FIGURE 6 Histogram of Clean Development Mechanism project efficiencies.

TABLE 2 Clean development mechanisms considered as benchmarks in Data Envelopment Analysis ranking.

Registration project title	Scale	Project type	Country
Bandeirantes Landfill Gas to Energy Project (BLFGE)	Large	Landfill gas	BR
Loma Los Colorados Landfill Gas Project	Large	Landfill gas	CL
Hasars Landfill Gas Project	Large	Landfill gas	MX
Proactiva Mérida Landfill Gas Capture and Flaring project	Large	Landfill gas	MX
Biogas energy plant from palm oil mill effluent	Small	Methane avoidance	GT
Anaerobic Biodigesters in the Yucatán Peninsula 1	Small	Methane avoidance	MX
Incauca S. A. Fuel Switch from Coal to Green Harvest Residues	Large	Biomass Energy	CO
Monterrey II LFG to Energy Project	Large	Landfill gas	MX
Monterrey I LFG to Energy Project	Large	Landfill gas	MX
Ferreira Gomes Hydro Power Plant	Large	Hydro	BR
Combined Cycle at Loma de la Lata Thermo Unit Project	Large	EE supply side	AR
Jirau Hydro Power Plant	Large	Hydro	BR
Teles Pires Hydropower Plant Project Activity	Large	Hydro	BR
Sogamoso Hydroelectric Project	Large	Hydro	CO

(financial investment and time) and output generation (installed capacity, emission reduction, and total CERs). Thus, the most efficient projects stand out by generating proportionally more outputs and/or consuming fewer inputs than others. In practice, this means that these are projects whose return (financial and environmental) is higher in relation to the investment made, making these projects more attractive to implement.

In this sense, from the results obtained with DEA, it is possible to perform comparative analyses to identify potential characteristics that differentiate more efficient projects from less efficient ones.

TABLE 3 Efficiency means and Mann–Whitney test results for project size and additional revenue.

		Mean efficiency (%)		Test results
Additional revenue	Sell Electricity	28.69	Mann–Whitney *U*	4022.00
	None	28.08	*p* value	0.626
Project size	Large (+)	33.35	Mann–Whitney *U*	1642.50
	Small	15.83	*p* value	0.00***

Note: Significant at *10%, **5%, and ***1%.

TABLE 4 Mean efficiencies and Mann–Whitney test results for different project types.

		Mean efficiency (%)		Test results
Project type	*Hydro* (−)	*20.05*	*Mann–Whitney U*	*2871.00*
	Others	*35.57*	*p value*	*0.00****
	Wind	2549	Mann–Whitney *U*	3220.00
	Others	29.41	*p* value	0.78
	Landfill gas (+)	*54.21*	*Mann–Whitney U*	*810.00*
	Others	*24.74*	*p value*	*0.00****
	Biomass energy (−)	*19.88*	*Mann–Whitney U*	*998.50*
	Others	*29.25*	*p value*	*0.062**
	EE supply side (+)	*59.99*	*Mann–Whitney U*	*188.50*
	Others	*27.44*	*p value*	*0.00****
	EE own generation	12.09	Mann–Whitney *U*	75.00
	Others	28.55	*p* value	0.72
	Geothermal	24.63	Mann–Whitney *U*	294.00
	Others	28.55	*p* value	0.48
	Methane avoidance (+)	*83.69*	*Mann–Whitney U*	*66.000*
	Others	*27.28*	*p value*	*0.00****
	Coal bed/mine methane	61.38	Mann–Whitney *U*	27.00
	Others	28.29	*p* value	0.29
	Solar	5.12	Mann–Whitney *U*	28.00
	Others	28.59	*p* value	0.30

Note: Significant at *10%, **5%, and ***1%.

To this end, a series of Mann–Whitney tests were conducted to compare the average efficiency of these projects, as presented in Tables 3, 4, and 5.

Table 3 presents the results of the Mann–Whitney tests for two variables: the project's capacity to generate additional revenue through the sale of generated energy and the scale of the project. As can be observed, regarding the first variable, there is no significant difference between projects that obtained additional revenue from energy sales and those that did not receive this type of financial resource. This aspect is particularly relevant because, according to Rahman and Kirkman,[35] energy generation is a valuable byproduct of CDM projects. Projects with these characteristics are considered less risky and therefore more attractive to investors. However, based on the findings, this is not a distinguishing feature that sets projects apart in terms of efficiency.

Concerning the second variable that is, the scale of the project (large or small), a statistically significant difference is found at a 0.01% level for large-scale projects, which exhibit superior efficiency compared to small-scale ones. Although this difference is expected, given that efficiency gains are common in large-scale operations, it is important to highlight that the DEA model used (Variable Return to Scale) already considers a possible disparity, relatively penalizing larger-scale projects, yet their efficiency is still significantly higher than that of small-scale projects. This result further strengthens the findings presented by Rahman et al.,[36] which concluded that there are reduced costs associated with energy generation as the duration and scale of CDM projects increase, thus making them more efficient. Another explored variable that can explain efficiency differences among energy generation CDM projects is the project type, as presented in Table 4.

Table 4 presents the results of Mann–Whitney tests for the average efficiency of the 10 types of projects considered by the UNFCCC. Out of these, five types showed statistically significant differences in efficiency compared to the others, with a significance level of 0.01%. Among them, the Methane Avoidance projects exhibited the highest difference in efficiency, with a rate of 83.69% compared to 27.28% for the other types. Methane Avoidance projects aim to reduce emissions or capture/utilize methane gas (CH4), thereby reducing its impact on the greenhouse effect. They rank as the fourth most

TABLE 5 Mean efficiencies and Mann–Whitney test results for different host countries.

		Average efficiency (%)		Test results
Host countries	Argentina (AR)	41.38	Mann–Whitney *U*	453.50
	Others	28.04	*p* value	0.46
	Bolivia (BO)	28.47	Mann–Whitney *U*	62.00
	Others	27.35	*p* value	0.55
	Brazil (BR)	30.50	Mann–Whitney *U*	3447.00
	Others	24.26	*p* value	0.14
	Chile (CL)	29.47	Mann–Whitney *U*	2125.50
	Others	22.91	*p* value	0.44
	Colombia (CO) (+)	*28.88*	*Mann–Whitney U*	*643.00*
	Others	*22.23*	*p value*	*0.02***
	Costa Rica (CR)	28.81	Mann–Whitney *U*	350.00
	Others	15.73	*p* value	0.35
	Cuba (CU)	28.15	Mann–Whitney *U*	85.00
	Others	57.72	*p* value	0.18
	Dominican Republic (DO)	28.81	Mann–Whitney *U*	127.00
	Others	7.17	*p* value	0.10
	Ecuador (EC)	28.58	Mann–Whitney *U*	432.00
	Others	24.16	*p* value	0.80
	Guatemala (GT)	28.21	Mann–Whitney *U*	437.50
	Others	36.16	*p* value	0.39
	Honduras (HN)	28.38	Mann–Whitney *U*	188.00
	Others	36.18	*p* value	0.99
	Jamaica (JM)	28.57	Mann–Whitney *U*	193.00
	Others	18.94	*p* value	0.95
	Mexico (MX) (+)	*46.83*	*Mann–Whitney U*	*1233.50*
	Others	*25.29*	*p value*	*0.00****
	Nicaragua (NI)	28.34	Mann–Whitney *U*	466.50
	Others	32.40	*p* value	0.52
	Panama (PA)	28.59	Mann–Whitney *U*	171.00
	Others	16.44	*p* value	0.83
	Peru (PE)	28.63	Mann–Whitney *U*	1182.00
	Others	26.33	*p* value	0.80
	El Salvador (SV)	28.30	Mann–Whitney *U*	197.00
	Others	38.99	*p* value	0.38
	Uruguay (UY)	28.72	Mann–Whitney *U*	49.50
	Others	4.87	*p* value	0.27

Note: Significant at *10%, **5%, and ***1%.

common type of CDM projects in Latin America that generate energy. This result can be attributed to two aspects, as reported by Lo and Cong[37] and Mori-Clement and Bednar-Friedl[38] in their findings. The first aspect is the fact that Methane Avoidance projects are generally small-scale projects that require low investment. The second aspect is the high capacity of generating Certified Emission Reductions (CERs) associated with these projects. Both of these aspects are included in the DEA (Data Envelopment Analysis) model used in this study, which contributes to the observed higher efficiency of Methane Avoidance projects compared to other types.

The second largest statistically significant difference in terms of efficiency is from Supply side energy efficiency improvement projects, with 59.99% compared to 27.44% for the others. These projects are related to the implementation of technologies or actions that reduce energy losses in their generation, transmission, or distribution, such as replacing transformers with higher performance ones or upgrading transmission line insulation. Although it is one of the least implemented types of CDM projects in Latin America (with only seven projects), according to Wu et al.,[39] it is one of the projects with the lowest relative cost per ton of greenhouse gas emissions reduction, which is due to its association with the use of simple technologies that require low investments.

The third type of project that exhibits a positive statistically significant difference is Landfill gas, with an efficiency of 54.21% compared to 24.74% for other types of CDMs. This type of project typically involves the capture and combustion of methane generated in landfills to generate energy. Kim et al.[40] emphasize that it is a type of CDM with one of the lowest costs related to infrastructure and maintenance, but with significant potential for GHG reduction, as 1 ton of methane is equivalent to 25 tons of CO_2eq. Another benefit of this type of project is the possibility of its implementation in municipal landfills, providing an additional source of revenue (through energy production or sale, or CERs) and jobs for the local community.

In the statistical tests conducted, two other types of projects showed significance at 0.01%, but with lower efficiency compared to others. These are Hydro Power projects, with 20.05% efficiency compared to 35.57% for other types of CDMs, and Biomass Energy projects, with 19.88% efficiency compared to 29.25% for the rest. In the case of Hydro Power projects, although Latin America has several regions with great hydraulic potential, according to Monteiro et al.,[41] these projects require very high initial costs, which possibly, in the model used in this study, negatively impacted their efficiency.

Regarding Biomass Energy projects, according to Rahman and Kirkman,[35] for a quantity of up to 80,000 CERs per year, emission reduction costs are more expensive compared to other projects. Since this is the majority of projects of this type within the sample, this aspect may have influenced the lower result in terms of efficiency.

The last variable in the UNFCCC's CDM database that can be explored is the country where the project was carried out. This is a relevant variable because it is possible to identify incentive policies and other factors that led to more efficient projects. Table 5 presents the results of the tests conducted for Latin American countries.

As seen in Table 5, only three countries showed statistically significant differences from the others. The first country to be highlighted is Mexico, which has an average project efficiency of 46.83%, compared to 25.29% for the rest, a result that is quite consistent since it is the country with the highest number of projects considered as benchmarks among the sample projects.

According to Corbera and Jover,[42] government initiatives for GHG reduction have been in place for over 20 years, starting with the creation of the Mexican Committee for the Reduction and Capture of GHG Emissions (COMEGEI). COMEGEI is a working group of the Intersecretarial Climate Change Commission and has been functioning as Mexico's Designated National Authority (DNA) since 2002. Its responsibilities include identifying investment opportunities for CDM projects and facilitating, promoting, and approving such projects.

Additionally, in 2007, the Mexican government established the Mexican Carbon Fund (FOMECAR) in partnership with a financial institution in the country. The aim of FOMECAR is to provide technical and financial support to private investors in the design of CDM projects. These government initiatives indicate the presence of concrete and long-term actions to promote the implementation of CDM projects in the country. This likely explains, at least in part, Mexico's performance in terms of efficiency compared to others.

Another country that stands out in terms of efficiency is Colombia, which has an average efficiency of 28.88% compared to 22.23% for the others. Similar to Mexico, the country has projects among the benchmarks found in the efficiency analysis, although in a smaller quantity, only 2. According to Duque et al.[43], Colombia has also implemented concrete environmental actions for a long time, with the development of the "Guidelines for Climate Change Policy," which outlined the main strategies to be adopted by the country for GHG mitigation, in the context of the Kyoto Protocol, of which it is a signatory. In the same year, the Colombian Office for the Mitigation of Climate Change was created, which was designated to promote all types of CDM projects.

Moreover, the authors emphasize that Colombia's rich endowment of natural resources and distinctive topographical features position it as a prime contender for the execution of alternative energy initiatives. Given its varied energy portfolio, the nation presents substantial prospects for engagement in the CDM.

5 | CONCLUSIONS, LIMITATIONS, AND FUTURE RESEARCH

This research aimed to address two research questions: First, which energy-generating CDM projects can be considered efficient in the Latin American context? Second, what are the characteristics that distinguish the most efficient projects from the least efficient ones?

To answer them, it was necessary to first identify which CDM energy-generating projects could be considered efficient in the context of Latin America, and then analyze the characteristics that differentiate the most efficient ones from the rest.

To accomplish this task, a publicly available database on Clean Development Mechanisms, provided by the United Nations Framework Convention on Climate Change (UNFCCC), was utilized. The data was processed to obtain a sample of 190 energy-generating CDM projects carried out in Latin America. With the data at hand, two analysis techniques were employed. The first was Data Envelopment Analysis, which facilitated the creation of an efficiency ranking among the projects. The second involved conducting non-parametric tests for mean comparison (Mann–Whitney) for the project-characterizing variables available in the utilized database.

The results obtained addressed the research questions and led to two conclusions. The first conclusion is that, according to the utilized model, the most efficient CCDM energy-generating projects in Latin America are: Bandeirantes Landfill Gas to Energy Project (BLFGE), Loma Los Colorados Landfill Gas Project, Hasars Landfill Gas Project, Proactiva Mérida Landfill Gas Capture and Flaring Project, Biogas energy plant from palm oil mill effluent, Anaerobic Biodigesters in the

Yucatán Peninsula 1, Incauca S. A. Fuel Switch from Coal to Green Harvest Residues, Monterrey II LFG to Energy Project, Monterrey I LFG to Energy Project, Ferreira Gomes Hydro Power Plant, Combined Cycle at Loma de la Lata Thermo Unit Project, Jirau Hydro Power Plant, Teles Pires Hydropower Plant Project Activity, Sogamoso Hydroelectric Project. All of these projects can easily be identified in the UNFCCC database available at https://cdm.unfccc.int/Statistics/Public/files/.

The second conclusion is that significantly more efficient energy-generating CDM projects are of large scale and fall into the following types (in descending order of average efficiency): Methane avoidance, Landfill gas, and Energy Efficiency Supply Side. It was also identified that projects of the Hydro and Biomass Energy types are significantly less efficient than the others. Additionally, projects carried out in Mexico and Colombia also exhibited significantly higher average efficiency than the rest.

Given the significance of CDM projects in reducing greenhouse gas emissions and contributing to energy generation, the findings presented here hold great relevance for both investors interested in participating in such projects in Latin America and public managers in the countries of this region.

In this context, a private investor fundamentally seeks to achieve returns on the projects they invest in. Typically, since these projects involve substantial financial commitments, economic and financial feasibility analyses—as well as risk assessments—are commonly conducted, considering aspects such as the Internal Rate of Return (IRR) or the project's Payback Period. However, in our analysis, the comparative efficiency results provide an alternative metric for decision-making, identifying that projects with the aforementioned characteristics yield higher "returns" (as expressed in the model by energy generation capacity and the sale of Certified Emission Reductions), while requiring proportionally less investment and shorter implementation time (represented in the model by capital invested and project duration). This offers potential investors an additional perspective that can be a key differentiator for the economic success of such initiatives.

On the other hand, for public managers and policymakers in Latin American countries interested in attracting investments in energy-generating CDM projects, they should consider creating incentives for projects that exhibit the highlighted characteristics associated with efficiency. These projects are more likely to yield greater returns and energy production capacity (which may be linked to job creation). Furthermore, in the case of Mexico and Colombia, identified as countries with superior average efficiency, these stakeholders should undertake a thorough analysis (beyond the aspects highlighted in this study) of the public management actions and policies that contributed to these countries' performance when compared to others in the region.

While the authors consider the results obtained in this study highly relevant, it's important to highlight certain limitations. The first limitation pertains to the database, which is not exhaustive in capturing all projects of this nature implemented in Latin America. In the original UNFCCC database, many projects had missing data, which are not suitable for use in Data Envelopment Analysis. Consequently, only a sample (albeit substantial in size) could be employed. Another limitation relates to the variables adopted in the model for distinguishing efficient and non-efficient projects. While the official database contains crucial information, it only provides a subset of characteristics for these projects, such as scale, additional income from energy sales, project type, and the country of implementation. Hence, it's important to emphasize that there could be other relevant characteristics that could not be explored in this study.

In this context, the authors recommend further studies to explore additional potentially relevant characteristics associated with the efficiency of energy-generating CDM projects. Specifically, we believe that factors such as local conditions (e.g., labor quality, incentives, suppliers, and government support), project complexity, and governance levels, in this order of priority, warrant investigation.

Additionally, it would be valuable to understand why certain types dominate the region and how they influence the energy matrix or sustainability goals. These aspects could be explored through surveys with project managers and policymakers or through case studies. Furthermore, the sample of projects from Latin America exhibits a high level of missing data. It is suggested that future studies examine the predominant characteristics of these observations to identify any patterns.

By delving into these aspects, researchers can gain a deeper understanding of the multifaceted factors that contribute to project efficiency. Such studies could enhance the comprehension of the broader context in which these projects operate and provide valuable insights for both private investors seeking profitable opportunities and public policymakers aiming to attract sustainable development investments in the Latin American region.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in Project Activities at https://cdm.unfccc.int/Projects/index.html. These data were derived from the following resources available in the public domain: CDM Pipeline, https://unepccc.org/cdm-ji-pipeline/.

ORCID

Antonio Carlos Pacagnella Junior https://orcid.org/0000-0003-4485-2777

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