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Applying a novel scoring approach to assess the success of waste management CDM projects by region, size, and subtype

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ABSTRACT

Greenhouse gas emission abatement is a primary objective of the Clean Development Mechanism (CDM) of the United Nations Framework Convention on Climate Change (UNFCCC) under the Kyoto Protocol. In this study, three criteria were developed and ascribed to CDM projects under sectoral scope 13, “waste handling and disposal”: 1) project performance; 2) specific costs for issued certified emission reductions (CERs); and 3) transition status to the Paris Agreement Crediting Mechanism (PACM) or a voluntary carbon offsetting program. Using the criteria and a success threshold, an aggregate scoring system was devised to rate the overarching “success” of each individual project. Finally, the projects were grouped by geographic subregion, project subtype, and size classification to observe success rate differences.

Of 280 projects evaluated, only 114 were assessed as being successful under this model (40.7 %). Projects in “Latin America and the Caribbean” were more than 1.5 times more likely to be evaluated as successful as projects in “Southeast Asia” and “Mainland Asia”. Projects classified as “large” were 1.8 times more likely to be evaluated as successful compared to projects classified as “small”. Projects managing “manure”, “landfill power”, and “landfill flaring” were more likely to be evaluated as successful as “waste water” projects.

The evaluation also showed that amongst the chosen criteria, cost-effectiveness is the least critical criterion for the success and longevity of the CDM projects. The developed novel scoring method provides a useful tool to assess the general project performance of CDM projects and could also be applied to other sectoral scopes.

1. Introduction

1.1. Background

The Kyoto Protocol (KP), which elaborated on the United Nations Framework Convention on Climate Change (UNFCCC), committed Annex I countries—primarily industrialized countries and countries with economies in transition—of the UNFCCC to legally binding emission reduction targets in a first commitment period from 2008 until 2012 (UNFCCC, 1997). This was set at 5 % below 1990 emission levels, but was specified on a per-country basis in Annex B of the Protocol (UNFCCC, 1997). A second commitment period from 2013 until 2020 was established by the Doha Amendment to the KP (UNFCCC, 2012). This committed participating countries to a more ambitious reduction of 18 % below 1990 emission levels (UNFCCC, 2012).

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To assist Annex I countries in meeting their targets under both commitment periods, the Kyoto Protocol established three flexible cooperation mechanisms: 1) the Clean Development Mechanism (CDM); 2) Joint Implementation (JI); and Emissions Trading (ET) (UNFCCC, 1997). The former two are project-based, allowing developed (Annex I) countries to invest in emission-reducing technology transfers to either developing (non-Annex I) countries or fellow Annex I countries for the CDM and JI, respectively (UNFCCC, 1997). Greenhouse gas (GHG) emission reductions could then be verified by independent Designated Operational Entities (DOEs) to generate carbon credits—labeled as certified emission reductions (CERs) under the CDM—that could be traded by Annex I countries via the carbon market established by the ET mechanism, for a combined benefit of low-cost GHG abatement and sustainable development outcomes (UNFCCC).

Under the Paris Agreement (PA), in contrast to the Kyoto Protocol, all signatories, including developing (non-Annex I) countries, have greenhouse gas emission commitments in the form of increasingly ambitious Nationally Determined Contributions (NDCs) (UNFCCC, 2016). This has necessitated the development of a second carbon crediting mechanism, given that developing country hosts may now wish to utilize generated credits from externally funded carbon projects to meet their own NDCs, in addition to the sustainable development benefits.

1.2. Literature review of previous studies

In their review paper, Bortoletto et al. (2023) took stock of the scientific literature on the Clean Development Mechanism to date. Among other things, they showed that project registrations under the CDM reached their peak in 2012—with 3234 projects—and dramatically decreased thereafter (Bortoletto et al., 2023). The average annual registration rate of 794 projects between 2004 and 2012 dropped to 87 projects between 2013 and 2020 (Bortoletto et al., 2023). This was precipitated by a number of factors, including the 2008 Financial Crisis, uncertainty around the future of GHG targets at the end of the first KP commitment period, and a sharp reduction in the market price of CERs (Bortoletto et al., 2023; Cantore, 2011; Michaelowa et al., 2021).

A loss of confidence in the long-term effectiveness of a market-based approach to incentivizing GHG emission abatement resulted (Bortoletto et al., 2023; Michaelowa, 2015). Debate ensued in the literature on the ultimate effectiveness of the CDM at accomplishing its goals: 1) to stabilize global GHG emissions and 2) to facilitate sustainable development (Bortoletto et al., 2023; UNFCCC, 1997).

Hultman et al. (2009), for example, argued that the CDM supports the implementation of a large number of projects, but that they are concentrated in specific regions and dominated by specific sectors. Additionally, even when large-scale projects might contribute more to GHG reductions, they generally do not offer significant benefits to local populations (Hultman et al., 2009). Similarly, Bumpus and Cole (2010) argued that a lack of transparency and a focus on the carbon market led to an estrangement of the sustainable development goal in project implementation. When referring to the Triple Bottom Line (TBL), Crowe (2013) argued that the vast majority of CDM projects prioritize the economic and environmental pillars but tend to neglect the social pillar.

By contrast, even with the acknowledgement of this overshadowing of the sustainable development goals within CDM project implementation, other authors have noted positive aspects of the CDM's legacy (Bortoletto et al., 2023). Examples include a decrease in China's emission output per unit GDP and overarching growth rate of CO_2 emissions that have been demonstrably linked to CDM project implementation (Shi et al., 2021); and individual countries' increase in competitiveness and innovativeness, especially as it relates to the renewable energy sector (Cui et al., 2020). Even with the criticism, many authors highlighted the myriad benefits of the developed-developing country technology transfers that did occur under the CDM. See Simon et al., 2017 and Schmid, 2012 for examples.

Attempts at assessing the broader effectiveness of Clean Development Mechanism projects are also represented in the literature. For example, Pacagnella Júnior et al. (2023), used a data envelope analysis (DEA) technique to determine the financial- and environmental efficiency of 2,352 projects. Lee et al. (2022) showed how the degree of ESG of a given host country affects the implementation of CDM projects. They concluded that energy-intensive industries and low sustainable energy outputs were drivers for successful project implementation; as were high unemployment rates coupled with lower undernourishment rates; as well as lower governance effectiveness coupled with a high rule of law (Lee et al., 2022).

Finally, attempts at analyzing or describing CDM projects within the waste management sector are also represented in the literature. Leelah and Mudhoo (2017) highlighted some of the barriers to project implementation in least developed countries in the waste management sector, arguing that a more inclusive framework that makes access to financing such programmes would increase the level of active participation of many developing countries in climate action. They also showed that 20 % of CERs in the waste sector had been canceled by the UNFCCC and encouraged further cancelations for true net reductions (Leelah and Mudhoo, 2017). Siebel et al. (2013) analyzed 400 project design documents (PDDs) of CDM projects in the waste management sector based on 50 sustainable waste management assessment indicators and scored them according to how well the indicators were represented in the project designs. They concluded a broader sustainability assessment dimension needs to be incorporated in the CDM framework to avoid scenarios that promote end-of-pipe GHG abatement solutions without addressing deeper sustainable waste management issues (Siebel et al., 2013).

This final paper serves as a concrete springboard for the work carried out in this paper.

1.3. Study relevance, objectives, and structure

The CDM is currently undergoing an unprecedented transition. Since the second commitment period of the Kyoto Protocol ended, eligible CDM projects wishing to transition to the new Paris Agreement Crediting Mechanism, were given until the end of 2023 to submit transition request applications for review and approval by the UNFCCC Secretariat and the Article 6.4 Supervisory Body, respectively (UNEP CCC, 2025a,b). Host countries have until the end of 2025 to approve these transition requests (UNEP CCC, 2025c).

This presents a unique opportunity to reflect on the past successes and shortcomings of the CDM, along with the future and fate of projects transitioning to the new mechanism under the Paris Agreement—especially regarding projects within sectoral scope 13, "waste handling and disposal" (UNFCCC, 2025). While multiple past studies have attempted to assess the success and impact of collections of CDM projects both within and outside the waste sector, via, for example, environmental- and financial efficiency, sustainability indicators, and social impacts (see previous subsection), none have attempted to assess the fate of CDM projects as they are confronted with the transition from one mechanism to another. Furthermore, there has been no attempt in the literature (to the authors' knowledge) to define "success" in the context of the CDM.

This gives the authors the opportunity to devise a novel scoring method, based on a multi-criterion analysis, which allows for the simple and efficient review and scoring of entire collections of projects without having to review individual project design documents. This would allow for the flagging of projects that have performed poorly and then allow for eventual follow-up investigations to determine the particularities of the failures, similar to a temperature sensor in a combustion engine. By defining "success" for the first time in the literature, this novel scoring method would also serve as an indicator for CDM projects and a vetting system for more detailed investigation of individual projects with reporting outcomes that go beyond normal parameters.

To initially guide the development of the novel scoring method, other established scoring and evaluation systems in similar fields were considered, with the two prime examples being the United Nations Framework Classification for Resources (UNFC) and parts 2 and 3 of ISO 14064 (UNECE, 2020; DIN, 2019a,b). It was noted, for example, that EN ISO 14064-3 was quoted directly within the CDM validation and verification standard for project activities, substantiating CER legitimacy and double-counting avoidance (UNFCCC). The UNFC was noted for its codification-style grading and its ability to demark potentially viable prospecting projects.

Additionally, by organizing scored projects by geography, type, and size, broader trends of success can be observed to inform more precise follow-up research questions, investment opportunities, or areas which need additional support. This would, in effect, serve as a precursor to a broader improvement of the CDM and similar mechanisms, especially as the international community completes its transition to the PACM, given that unusually unsuccessful or even exceptionally successful projects that might have gone otherwise unnoticed can be quickly and efficiently identified for further review and extrapolation of valuable information to guide future policies surrounding such projects. Finally, it is a method which can be easily applied to other sectoral scopes or the entire body of CDM projects.

As such, by accessing the database of all CDM projects (UNFCCC, 2024), this study set out to fulfill the following objectives:

Objective 1: Assess the broader performance of sectoral scope 13 projects using three criteria (project performance, specific CER costs, transition potential);

Objective 2: Apply the novel scoring method to determine project-level success and identify the proportion of successful projects; and.

Objective 3: Identify patterns in project success across geographic subregions, size classes, and project subtypes.

This was done to quantify broader success—or lack thereof—within the CDM and to monitor the fate of projects that did not successfully transition to a new carbon crediting mechanism (Paris Agreement or voluntary).

The paper details which data sources were employed (section 2.1) and how CDM projects were selected for analysis. Section 2.2 describes the novel scoring method, presents the three defined scores, and shows how the grading scale with a "success" threshold indicator was applied to the aggregate project scores. Section 2.3 then describes how the results were organized by category for pattern identification (subregion, project size, project subtype). The results and discussion section present the results based on the study objectives, starting with the raw results of the three individual criteria, then success rates of projects after the scoring model was applied, and ending with the aggregated scores as grouped based on the three predetermined categories.

2. Materials and methods

2.1. Data sources

This work utilized the UNFCCC's "Database for PAs and PoAs" (UNFCCC, 2024), the "CDM Pipeline" (UNEP CCC, 2025c), and the Berkeley "Voluntary Registry Offsets Database" (Haya et al., 2025). How they were used is described in the supplementary information S1.

2.2. Development of a novel scoring model

2.2.1. Description and rationale of the scoring system

Three criteria were selected for the novel grading system, namely, 1) Project performance, as represented by the quotient described in section 2.2.2; 2) Specific CER costs, as determined in section 2.2.3; and 3) Project transition potential, per the PACM or a voluntary carbon offset program, as described in section 2.2.4. The criteria were selected to simply but adequately represent three grading categories, namely, environmental impact (via issued CERs); economic sustainability (i.e., to what extent are generated credits cost-effective and/or reasonably aligned with expected market prices); and project longevity and durability (i.e., is the project reasonably expected to continue into the future and generate the ex-ante quantities of CERs determined in the PDD).

For projects to be included in the sample size, they needed to be 1) under sectoral scope 13, "waste handling and disposal" (including all methodologies thereunder); 2) have a website project status of "Registered"; 3) have reported ex-ante reductions (per the project design document (PDD)); and 4) have at least one issuance of certified emission reductions (CER). Additionally, projects had to have 5) reported “Total capital investment (USD)" or “Total O&M costs (USD/year)" to be included. Of the 963 registered projects under sectoral scope 13, 428 were pre-filtered for the project performance quotient (1–4), and 280 were filtered further for specific CER costs (5). This became the final sample size for analysis. Transition potential data was available for all projects and didn’t affect the sample size.

Each category was assigned equal weight. Therefore, for each criterion a score of between 0 and 1/3 was assigned. The scoring scales ascribed to each individual criterion are described in the subsequent chapters. Ultimately, these three scores were combined from each project to derive an individual aggregate score between 0 and 1. A grading scale was then applied to the aggregate scores for the sake of categorization, ranking, and discussion.

The grading categories were given equal weight, given that if all three are satisfactorily fulfilled, then the impact of the project will likely be maximized. If more than 1/3 of the aggregate score was missing, it was assumed that its environmental impact, economic sustainability, or ability to maintain its impact into the future were lacking and/or insufficient. The primary exception to this were projects that were, by design, intended to be implemented for a set period. This is described in more detail in section 2.2.4.

2.2.2. Score 1: project performance quotient (PP_{quo})

A project’s performance was measured by comparing the number of issued CERs with the expected reductions stated in the PDD for the entire project duration. In other words, it compared actual CERs generated to the planned CER output. Each credit period was cut off exactly on October 10, 2024, the last date the dataset was updated at the time of the analysis. If a credit period exceeded this cutoff date, then the total planned CERs were proportionally reduced to the respective credit period until the cutoff date.

Projects could run over three possible, separate credit periods (CP). The crediting periods do not correspond with the commitment periods of the Kyoto Protocol and its Doha Amendment, respectively (that is, 2008–2012 and 2013–2020) (UNFCCC, 1997; UNFCCC, 2012), given that projects were registered and implemented at different times within these commitment periods. If a project had a third crediting period, it started most often beyond 2020, when the transition to the Paris Agreement was underway.

The project performance quotient (PP_{quo}) was then derived by dividing the “Total CERs issued” by the determined “TOTAL ex-ante Reductions for CP1-CP3 (until Oct 10, 2024)” for all projects. This resulted in a value between 0 and 1.

From there, the project performance quotient (PP_{quo}) of each individual project was converted to a score between 0 and 1/3 with the following scale.

If $PP_{quo} \leq 0.1$, then 0
If $PP_{quo} > 0.1$ and ≤ 0.3, then $(1/3)/5 \rightarrow 0.07$
If $PP_{quo} > 0.3$ and ≤ 0.5, then $2 * ((1/3)/5) \rightarrow 0.13$
If $PP_{quo} > 0.5$ and ≤ 0.7, then $3 * ((1/3)/5) \rightarrow 0.20$
If $PP_{quo} > 0.7$ and ≤ 0.9, then $4 * ((1/3)/5) \rightarrow 0.27$
If $PP_{quo} > 0.9$, then $1/3 \rightarrow 0.33$

The scores are rounded here to two decimal places, but exact values were used for the actual aggregate scores.

2.2.3. Score 2: specific certified emission reduction cost ($CER_{\$}$)

Specific CER costs were determined with Equation (1):

$$CER_{\$} = \frac{(NPV_{CAPEX} + (OPEX \times (CP_1 + CP_2 + CP_3)) - REV)}{CER_i} \tag{1}$$

Where:

$CER_{\$}$ = Specific cost per certified emission reduction (USD/CER_i).
NPV_{CAPEX} = Net present value of total capital investment (USD).
OPEX = Annual operating and maintenance costs (USD/year).
CP_X = Crediting period “x” given in years.
REV = Total project revenues (USD).
CER_i = Total issued certified emission reductions.
Please note that one CER represents 1 metric ton of CO_2eq.

Net present values of total capital investments were determined with Equation (2):

$$NPV_{CAPEX} = \frac{CAPEX}{(1+i)^{t/2}} \tag{2}$$

Where:

NPV_{CAPEX} = Net present value of total capital investment (USD).
CAPEX = Total capital investment (USD).
i = Discount rate

t = Average project duration (years).

An average annual interest rate of 5 % was selected as the discount rate. This value was chosen to also match and/or outpace the global inflation rate. The average project duration across the original sample size of 428 projects was determined to be 10.3 years.

This is an oversimplification of the net present value, given that it was only ascribed to the investment costs and does not consider all cash flows. However, in the absence of annually reported revenues and other financial data inputs for most projects, it was decided that adjusting the investment costs (at the very least) would be an impactful and consistent way to arrive at the most accurate specific CER costs.

Similar to the project performance quotient, the specific CER cost of each individual project ($CER_\$$) was then converted to a score between 0 and 1/3 with the following scale.

If $CER_\$ > 150$, then 0
If $CER_\$ > 120$ and ≤ 150, then $(1/3)/5 \rightarrow 0.07$
If $CER_\$ > 90$ and ≤ 120, then $2 * ((1/3)/5) \rightarrow 0.13$
If $CER_\$ > 60$ and ≤ 90, then $3 * ((1/3)/5) \rightarrow 0.20$
If $CER_\$ > 30$ and ≤ 60, then $4 * ((1/3)/5) \rightarrow 0.27$
If $CER_\$ \leq 30$, then $1/3 \rightarrow 0.33$

The ranges of the scale are in USD. The scores are rounded here to two decimal places, but exact values were used for the actual aggregate scores.

According to Fearnehough et al. (2018), the upper limit of the secondary market value of CERs never quite reached 30 Euros. Although the average exchange rate from EUR to USD of 1.18 in 2018, would put this value at about 35 USD (ECB, 2025), other sources show that both the secondary market value and the primary market value of CERs never reached 30 USD and 16 USD, respectively, between 2004 and 2020/2021, respectively (Michaelowa et al., 2021; Luomi et al., 2023).

Even with some discrepancy and uncertainty in the literature, 30 USD was elected as the lower limit for the scoring model, as it was deemed that if the specific costs of CERs were 30 USD or below, then the costs recovered from their sale would be, at least in part, appropriately aligned with the market value.

The upper limit of 150 USD for the scoring model was based on the carbon credit values globally provided by the World Bank's Carbon Pricing Dashboard (World Bank, 2025a), along with loose consideration of the spread of specific CER costs across the sample size. While it is rare for even "high quality" carbon credits to sell for 150 USD (Hewlett et al., 2024), it is not totally implausible, and this limit was set to be realistic on the one hand, but on the other hand, forgiving to a non-normal distribution where many extreme values were observed (i.e., multiple orders of magnitude). More expensive, "high quality" carbon credits might also represent smaller-scale projects that have lower emission reductions but a higher development impact (Hewlett et al., 2024).

Specific CER costs are not wholly representative of the economic sustainability of any given project. However, specific CER costs were viewed as an indicator of economic sustainability rather than a designation of it.

2.2.4. *Score 3: transition potential*

Scores of 0 or 1/3 were ascribed based on transition status either to the Paris Agreement Crediting Mechanism (PACM) or to a voluntary carbon offset program with the decision tree shown in Fig. 1.

During data collection, it was found that some projects that had transitioned to non-UN carbon offset programs had also submitted a

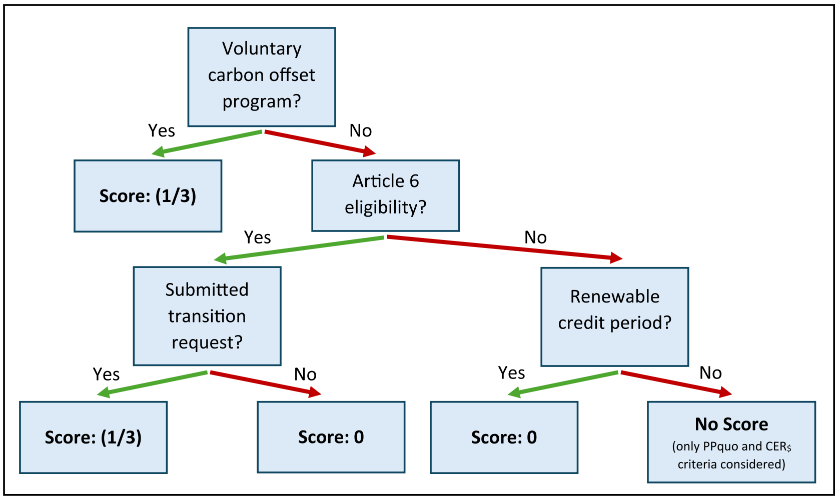

Fig. 1. Transition to other carbon offset mechanism scoring decision tree.

transition request for the PACM. It is unclear if the projects will terminate their involvement in a voluntary program if they're ultimately accepted to the PACM, but having this as the first question in the decision tree eliminated projects being evaluated twice. Both transitions were, either way, awarded full points.

If projects were eligible for the new crediting mechanism under Article 6.4 of the Paris Agreement, then they were evaluated as to whether they submitted a transition request to the Article 6.4 Supervisory Board or not. Full points were awarded to those that did, and no points were awarded to those that failed to do so.

Those projects that were not eligible for the PACM were evaluated as to whether they had a renewable or fixed crediting period. No points were awarded to those projects with a renewable CP, and no score was given for those with a fixed CP. Projects with a fixed crediting period were presumed to have been "ineligible for Article 6.4 by design". Therefore, the third scoring category in these cases was removed and these projects were evaluated exclusively based on their project performance and specific CER costs (both adjusted to be weighted at 50 %; see supplementary information S5).

Both a failure to submit a transition request and a failure to be eligible for the PACM when a project had a renewable crediting period were deemed as being failures of fulfilling the full potential of the project. The assumption regarding the renewable crediting period was that a project could have renewed its project to qualify for the new Article 6.4 mechanism but didn't. Theoretically, all project activities (PAs) and programmes of activities (PoAs) under the CDM could have qualified for Article 6.4, as long as they had an active crediting period on or after January 1, 2021 (UNEP CCC, 2025c).

While a more robust scoring system would already denote all the projects that have successfully transitioned to the PACM, this transition is still in progress and will not be finalized until the end of 2025 (UNEP CCC, 2025b), so the transition requests were viewed as an indicator of probable final transition.

If a project could have transitioned to the PACM or a voluntary credit offset program, and did not, then it does not necessarily need to be the case that the project will cease to exist or cease to reduce net GHG emissions. The reductions just may not be documented at an international level any longer. Additionally, while the Berkeley database is close to comprehensive, representing 99.4 % of all voluntary carbon offsets worldwide (June 2023), a couple of exceptions are present, namely, Plan Vivo (0.5 %), GCC (<0.1 %), and Climate Forward (<0.1 %) (Dyck et al., 2023). Plausibly, some projects in sectoral scope 13 transitioned to one of these voluntary programs or others and have been falsely ascribed "0 points" for not transitioning.

2.2.5. *Grading scale of aggregate project scores*

Ultimately, the three criterion scores for a given project were aggregated to give a total value between 0 and 1. These scores were then grouped according to the following grading scale:

If score $\geq$0.8, then "Most successful"
If score $\geq$0.6, then "Successful"
If score $\geq$0.4, then "Operational".
If score $\geq$0.2, then "Marginally operational".
If score $<$0.2, then "Inoperative/Ineffectual".

While the labels for these groups are somewhat arbitrary, it was important to be able to classify them to be able to rank and compare them. To achieve a score of 0.8 or higher ("Most successful"), no individual score could fall below 0.13. If any project had an aggregate score of 0.6 or higher, then it was determined to be "successful" by this scoring model. This threshold of 0.6 was chosen in order to consider projects which achieved a full score for at least one criterion. Given that the transition score was awarded either full or no points, some projects could be labeled "successful" with one criterion being zero. However, this was only true for 9 of 280 projects (see Figs. 4–6 in results). The overall success rate was determined as the ratio of successful projects to the sample size.

The scored, graded projects were then classified based on geographic subregion, size, and project subtype, to determine if these classifications bore any weight on a project's likelihood to succeed or perform well.

2.3. *Grouping of projects*

2.3.1. *Project geographic subregions*

The United Nations Statistics Division (UNSD) defines six continental regions and 22 geographic subregions, with two "intermediary regions", under which multiple subregions are grouped (UNSD, 2025). Given that the authors have a vested interest in project phenomena in Sub-Saharan African countries for future analyses that go beyond the scope of this paper, it was decided to maintain the first intermediary region, "Sub-Saharan Africa", which groups the subregions, "Western Africa", "Middle Africa", "Eastern Africa", and "Southern Africa" together. This was abbreviated as "SSA". Similarly, the second intermediary region, "Latin America and the Caribbean", was also maintained, which groups the subregions, "Caribbean", "Central America", and "South America". This was abbreviated as "LAC".

Otherwise, the subregions were adapted as the following:

"Western Asia" and "Northern Africa" were grouped together as "Middle East and North Africa" and abbreviated as "MENA". The MENA subregion usually does not include Turkey, Cyprus, or former Soviet states, but this was accepted as a limitation of the analysis for the sake of preserving the UNSD geographic subregions (World Bank, 2025b).

"Central Asia", "Eastern Asia", and "Southern Asia" were grouped together and labeled as "Mainland Asia".

"Micronesia", "Polynesia", "Melanesia", and "Australia and New Zealand" were grouped together and labeled as "Oceania".

Once final criteria were applied, qualifying projects were not observed in “Northern America”, “Western Europe”, “Northern Europe”, “Eastern Europe”, or “Southern Europe”. Please see the supplementary information (Fig. S1) for additional details on the adaptation of subregions.

2.3.2. Project size

Projects were grouped into “Large” and “Small”. According to Decision 1 of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol on its second session (CMP.2), small-scale projects under the CDM were revised to be defined as the following (UNFCCC, 2007):

(a) “Type I project activities shall remain the same, such that renewable energy project activities shall have a maximum output capacity of 15 MW (or an appropriate equivalent);
(b) Type II project activities or those relating to improvements in energy efficiency which reduce energy consumption, on the supply and/or demand side, shall be limited to those with a maximum output of 60 GWh per year (or an appropriate equivalent);
(c) Type III project activities, otherwise known as other project activities, shall be limited to those that result in emission reductions of less than or equal to 60 kt CO_2 equivalent annually; ”

Any other project activities that do not fulfill these criteria are considered large-scale.

2.3.3. Project subtypes

Within the CDM, there are more than 250 approved methodologies for greenhouse gas (GHG) emission abatement (Gold Standard, 2023). Those methodologies are linked to the fifteen sectoral scopes, with many methodologies being linked to more than just one sectoral scope (UNFCCC, 2025). The projects that use any given methodology are then classified by project type and subtype defined by the UNEP DTU Partnership (now UNEP CCC) (UNEP CCC, 2025b). There are approximately 30 project types and around 170 project subtypes (UNFCCC, 2024). Upon inclusion of projects from sectoral scope 13 for this work, 3 project types (“Biomass energy”, “Landfill gas”, and “Methane avoidance”) and 15 project subtypes were included for analysis. Those project subtypes are briefly described in S3 of the supplementary information under their respective project types.

3. Results and discussion

To ensure clarity and alignment with the study objectives, this section is structured to explicitly address each objective defined in Section 1.3.

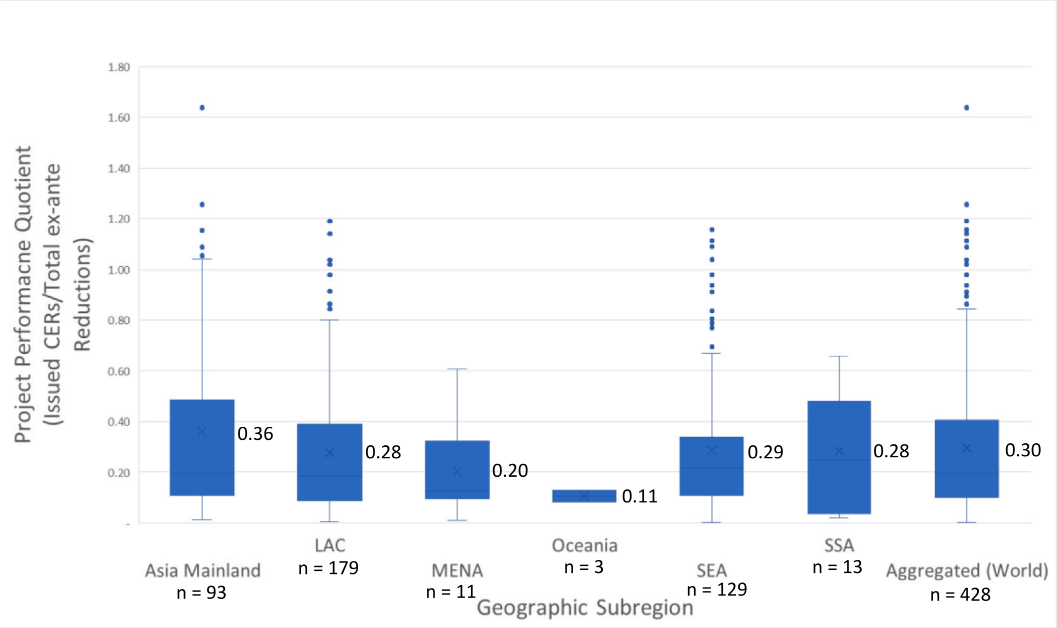

Fig. 2. Project performance distribution by geographic subregion.

3.1. Overall performance of CDM waste projects (objective 1)

3.1.1. Project performance quotient

Fig. 2 shows that on average the project performance quotient among the 428 considered projects is 0.30. Thus, on average only 30 % of design CER output was actually issued. However, there is a large amount of variation amongst the projects, indicated by, for example, the overarching median of 0.20 and a standard deviation of 0.28. Only 22 projects (5.1 %) reached the design CER output or over performed (Project Performance Quotient ≥ 1; this included projects that would round up to 1; i.e., ≥ 0.95). These projects all fall beyond the statistical upper limit of 0.86 and are considered outliers. With half of the projects having a project performance less than or equal to 0.20, this criterion, on average, lowered the aggregate scores of projects (see Fig. 4 through Fig. 6). Ultimately, of the expected ~564M CER output volume (ex-ante reductions) of this sample, only ~198M CERs (35 %) were issued.

3.1.2. Specific CER costs

The specific CER costs (Table 1) varied extremely among the considered projects (from $0.12 to $12,742 per CER) with an overall average of $154 per CER. The highest average was found for projects in Southeast Asia with $265 and the lowest in MENA with $41.7 per CER. In total, 56.8 % (159 projects out of 280) had specific costs of less than or equal to $30 per CER. Fig. 3 shows that these 159 projects issued 90.6 % of the total issued CERs (~106M of ~117M). The difference between the share of projects with specific CER costs of ≤$30 (56.8 %) and the share of CERs issued with ≤$30 (90.6 %) already indicates that rather larger projects (with high CER output) performed well in regard to cost-effectiveness. Another 83 projects (29.6 %) fell within the >$30 to ≤$150 range, accounting for another 8.2 % of the total issued CER volume (see Fig. 3); leaving only 1.2 % of the total issued CER volume for the remaining 38 projects (13.6 %) with >$150 CER specific costs. This indicates that the majority of emission reductions were achieved cost-effectively, thus, there is a strong potential for certified waste-related projects to deliver low-cost CO_2 mitigation.

It was also observed that there is a significant negative relationship between the project performance quotient and the specific CER costs (p-value <0.05) (see supplementary information S4). That is, as project performance goes up, specific CER costs go down. This also indicates that cost-efficient CERs were issued when there was a high CER output. Nevertheless, it is clear to see that the observed extreme values skewed the average and curve of the distribution substantially, as shown by the values presented in Table 1. See supplementary information for more details (Fig. S2).

As per the grading scale described in section 2.2.5, it can be concluded that cost effectiveness was not always a major limitation, especially as compared to project performance and transition potential. That is, specific CER costs, at least in part, contributed to raising the average success rate based on this grading model. This is consistent with past research which has shown that waste management projects are generally economically cost-effective. For examples, see Iqbal et al. (2024), Sasao (2020), and Wang et al. (2016).

3.1.3. Transition to a new carbon offset mechanism

Table 2 shows that, across 428 projects, 114 (27 %) fulfilled the transition criteria applied within this novel scoring model ("Combined Transitioning" in Table 2). Note that the combined transitioning project total is not the absolute sum of the projects which submitted PACM transition requests or transitioned to a voluntary carbon market program, because there were cases of overlap between the two (16 overall). Of 151 projects eligible for the transition to the PACM, 69 (16 %) submitted transition requests. Within the voluntary market, 61 projects (14 %) were identified. 167 projects (39 %) did not fulfill the transition criteria (score of 0)—i.e., theoretically could have transitioned to the PACM or a voluntary carbon offset program and didn't. 147 projects (34 %) were considered neutral, being likely ineligible to transition because of project design (no score for transition; such projects were only evaluated based on PP_{quo} and $CER_{\$}$; see supplementary information S5).

3.2. Application of the scoring model and overall success rate (objective 2)

Applying the equal-weighted scoring model, 114 of 280 projects (40.7 %) achieved an aggregate score ≥0.6 and were therefore classified as "successful" (see far-right columns of Tables 3–5 in section 3.3 for more detail). Within this group, 43 projects met the criteria for "Most Successful" (≥0.8). By contrast, 93 projects (33.2 %) were classified as marginally operational or inoperative (<0.4). 67 of 280 projects transitioned or are about to transition (23.9 %) to another carbon offset program and thus got full points for the transition score. Of the 114 "successful" projects identified (aggregate score ≥0,6), 53 projects scored in all three of the defined criteria (18.9 %).

Table 1

Specific CER cost distribution by geographic subregion.

Sub-region	Sample Size	Min ($/CER)	Median ($/CER)	Max ($/CER)	Outliers (#)	Avg ($/CER)	Std Dev ($/CER)
Asia Mainland	n = 69	$3.3	$49.2	$1,699	4	$135	$263
Latin America & Caribbean (LAC)	n = 105	$0.12	$6.6	$3,466	16	$84.2	$375
Middle East&North Africa (MENA)	n = 6	$4.0	$10.4	$139	0	$41.7	$55.6
Oceania	n = 2	$90.7	$96.0	$101	0	$96.0	$7.5
Southeast Asia (SEA)	n = 91	$3.4	$34.1	$12,742	10	$265	$1,355
Sub-Saharan Africa (SSA)	n = 7	$3.7	$10.0	$445	1	$76.4	$163
Aggregated (World)	n = 280	$0.12	$24.3	$12,742	30	$154	$818

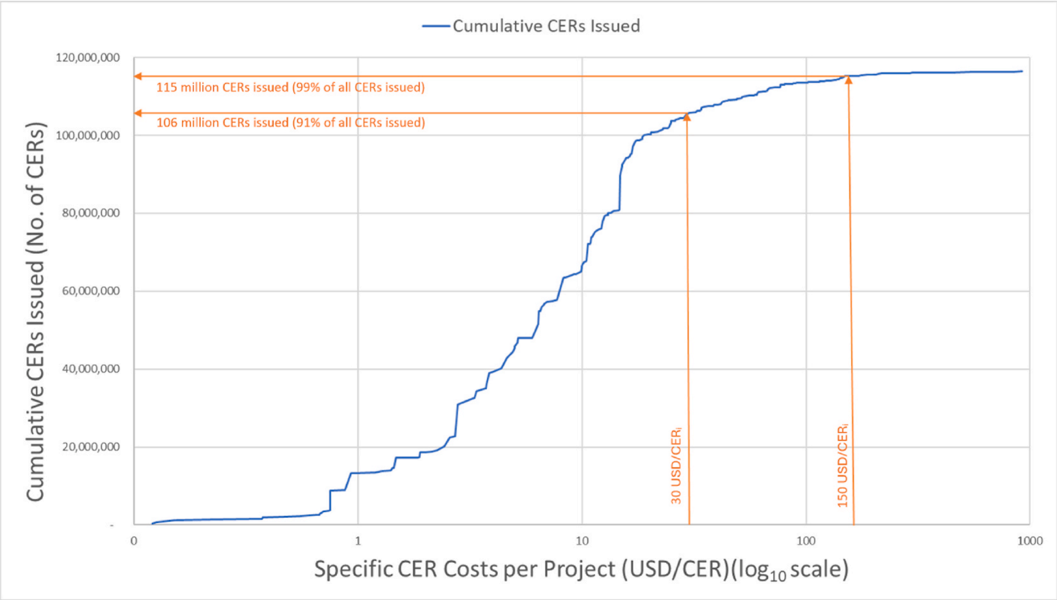

Fig. 3. Cumulative CER Volume vs. Individual Project Specific CER Costs (n = 280 projects). The orange horizontal and vertical lines denote the cumulative volume of issued CERs for all projects with a CER cost of ≤30 USD/CER and ≤150 USD/CER, respectively. For the sake of x-axis interval consistency, the final 8 projects with CER costs ≥1000 USD/CER were not plotted.

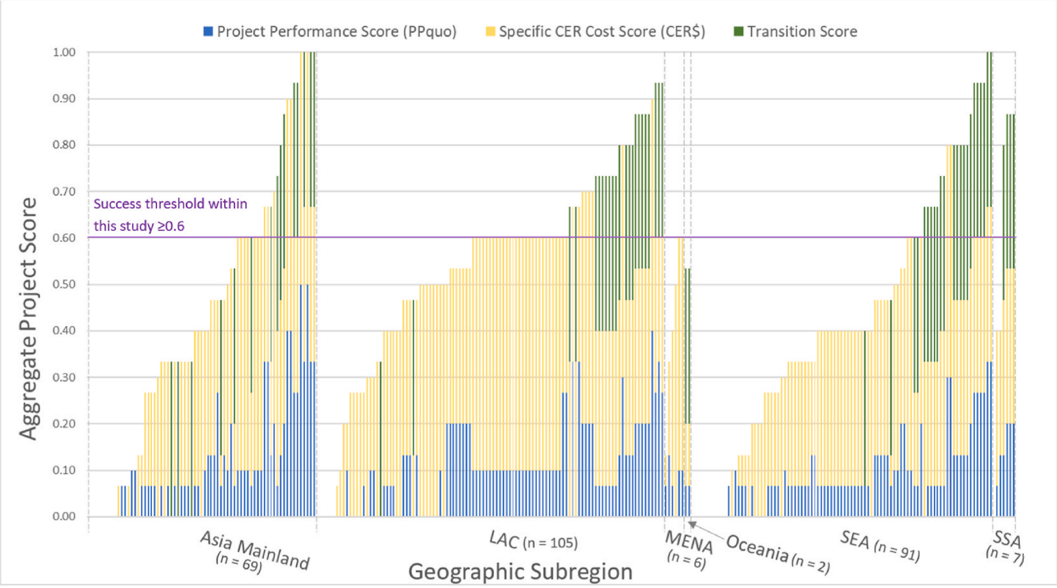

Fig. 4. CDM waste project aggregate scores by geographic subregion. The success threshold of 0.6 is denoted by the horizontal purple/dark line. All bars reaching or surpassing this threshold were considered “successful” within this study. Please note that “gaps” represent projects with a score of 0.

The application of the model thus demonstrates that, under the defined criteria, less than half of all waste-sector CDM projects can be deemed successful, primarily due to shortcomings in project performance quotient (PPquo) and transition potential rather than CER cost-effectiveness.

This directly fulfills Objective 2: the scoring method produced a clear, interpretable classification of project success across a large dataset.

Eventually, identifying a fourth indicator to represent sustainable development resulting from implemented projects would be a warranted improvement. An example would be whether or not a host country has a national procedure for stakeholder consultations, which has been shown to be a marker of higher economic and social impact on the local population (Benites-Lazaro and Mello-Théry,

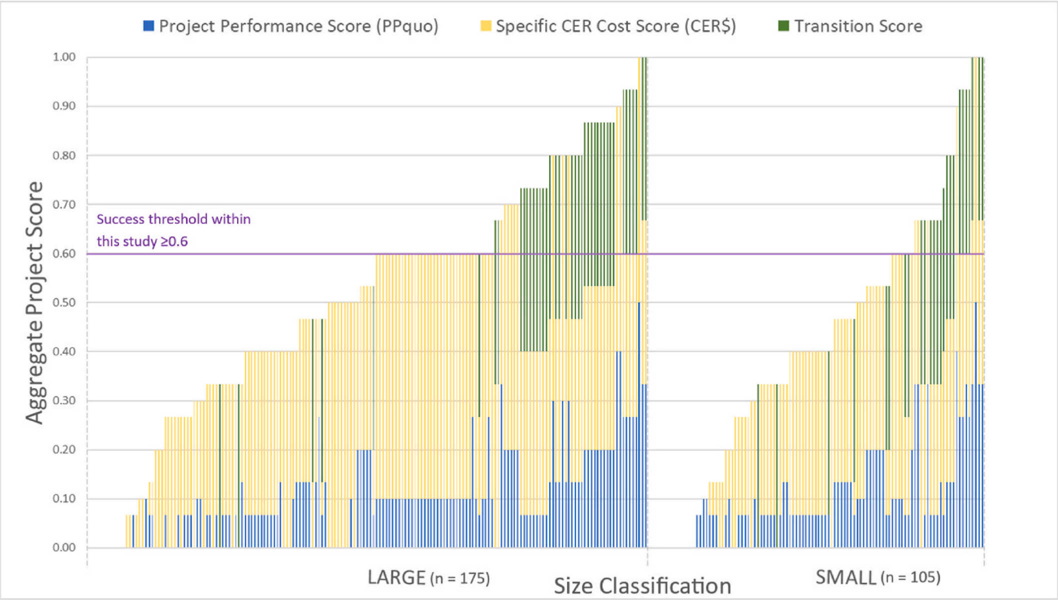

Fig. 5. CDM Waste project aggregate scores by project size classification. The success threshold of 0.6 is denoted by the horizontal purple/dark line. All bars reaching or surpassing this threshold were considered "successful" within this study. Please note that "gaps" represent projects with a score of 0.

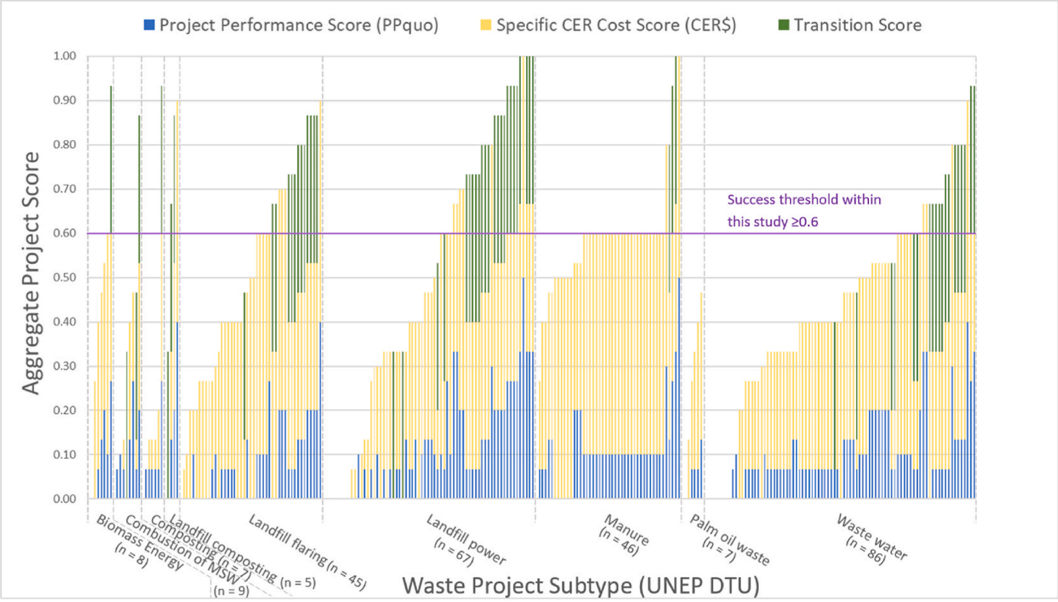

Fig. 6. CDM waste project aggregate scores by project subtype. The success threshold of 0.6 is denoted by the horizontal purple/dark line. All bars reaching or surpassing this threshold were considered "successful" within this study. Please note that "gaps" represent projects with a score of 0.

2019). Additionally, while this scoring model attempted to utilize ex-post data for primarily GHG mitigation and overarching economic sustainability, an ex-post study that complements Siebel et al.'s (2013) comprehensive ex-ante analysis of sustainable waste management indicators in 400 PDD's is still missing.

Regarding the scoring model itself, a codification scoring system, like that of the United Nations Framework Classification for Resources, was considered as an alternative to an aggregate scoring system (UNECE, 2020). The benefit of such a system is that discrete units provide scores that are more descriptive in nature than determinative. Ultimately, this was not preferred, given that such a scoring system is intended to assess prospective projects and not already existing ones (UNECE, 2020).

Table 2

Project transitions to other carbon offset mechanisms by geographic sub-region.

Sub-region	Sample Size	Submitted PACM Transition Request (#)	Voluntary Carbon Program Transition (#)	Combined Transitioning Project Total (#)	Failure to Transition (#)	Non-eligible projects w/fixed CP (#)
Asia Mainland	n = 93	6	19	23	43	27
Latin America & Caribbean	n = 179	37	12	40	45	94
Middle East & North Africa	n = 11	0	0	0	7	4
Oceania	n = 3	0	2	2	1	0
Southeast Asia	n = 129	20	24	42	66	21
Sub-Saharan Africa	n = 13	6	4	7	5	1
World Aggregated	n = 428	69	61	114	167	147
World Aggregated - Relative	n = 428	16 %	14 %	27 %	39 %	34 %

Table 3

Breakdown of scoring categories by geographic subregion. only subgroupings with a sample size greater than 20 are considered for discussion and interpretation. These are bolded in the table accordingly for more seamless recognition.

Scoring Categories	Asia Mainland Counts	LAC Counts	MENA Counts	Oceania Counts	SEA Counts	SSA Counts	Total Counts
Most Successful (≥0.8)	11	14	0	0	14	4	43
Successful (<0.8, ≥0.6)	13	44	2	0	12	0	71
Operational (<0.6, ≥0.4)	13	27	2	2	27	2	73
Marginally Operational (<0.4, ≥0.2)	15	12	1	0	20	0	48
Inoperative/Ineffectual (<0.2)	17	8	1	0	18	1	45
Sample size	**69**	**105**	6	2	**91**	7	280
No. successful projects (score ≥0.6)	24	58	2	0	26	4	114
Overall success rate	**35 %**	**55 %**	33 %	0 %	**29 %**	57 %	41 %

Table 4

Breakdown of scoring categories by size classification.

Scoring Categories	Large Counts[a]	Small Counts[a]	Total Counts
Most Successful (≥0.8)	31 (72 %)	12 (28 %)	43
Successful (<0.8, ≥0.6)	54 (76 %)	17 (24 %)	71
Operational (<0.6, ≥0.4)	41 (56 %)	32 (44 %)	73
Marginally Operational (<0.4, ≥0.2)	28 (58 %)	20 (42 %)	48
Inoperative/Ineffectual (<0.2)	21 (46 %)	24 (53 %)	45
Sample size	**175** (62.5 %)	**105** (37.5 %)	280
No. successful projects (score ≥0.6)	85	29	114
Overall success rate	**49 %**	**28 %**	41 %

[a] Values in parentheses represent the percentage of the total count amongst the respective scoring category.

3.3. Determinants of project success (objective 3)

3.3.1. Geographic patterns

The total project scores depending on geographic subregion are presented in Fig. 4 and Table 3. According to the defined grading model and its success threshold of 0.6, the largest shares of successful projects were found in Sub-Saharan Africa (SSA) and Latin America and Caribbean (LAC), with overall success rates of 57 % and 55 %, respectively (Table 3). However, the sample size of SSA was small with only 7 projects total (from which 4 were “Most Successful”). In total, 43 project were classified as “Most Successful”, from which a similar absolute number of projects was found in Asia Mainland, LAC and SEA (between 11 and 14 projects each).

Based on the results, projects in LAC were 1.9 and 1.6 times more likely to be successful than projects in Southeast Asia and Asia Mainland, respectively. This might be explained by the fact that 96 of 105 LAC projects were classified as being “Large” (and 95 % of the successful projects in LAC are “Large”). Additionally, 41, 32, and 21 (94 total) of 105 LAC projects fell under the project subtypes manure, landfill flaring, and landfill power, respectively. Apart from four projects, all successful LAC projects dealt with manure, landfill flaring or landfill power. As will be seen in the subsequent sections, each of these classifications were also more likely to succeed than others.

However, while LAC projects were found to be more successful, a closer look is justified due to findings by (Benites-Lazaro and Mello-Théry, 2019; Mori-Clement, 2019), who both assess the claimed sustainable developments benefits of the projects in the region,

Table 5

Breakdown of Scoring Categories by Project Subtype. Only subgroupings with a sample size greater than 20 are considered for discussion and interpretation. These are bolded in the table accordingly for more seamless recognition.

Scoring Categories	Biomass Energy Counts	Combustion of MSW Counts	Composting Counts	Landfill Composting Counts	Landfill Flaring Counts	Landfill Power Counts	Manure Counts	Palm Oil Waste Counts	Waste Water Counts	Total Counts
Most Successful (≥0.8)	1	1	1	2	8	17	5	0	8	43
Successful (<0.8 ≥ 0.6)	1	0	0	1	13	13	26	0	17	71
Operational (<0.6 ≥ 0.4)	3	3	0	0	11	10	13	2	31	73
Marginally Operational (<0.4 ≥ 0.2)	1	1	1	1	10	12	1	2	19	48
Inoperative/ Ineffectual (<0.2)	2	4	5	1	3	15	1	3	11	45
Sample size	8	9	7	5	**45**	**67**	**46**	7	**86**	280
No. successful projects (≥0.6)	2	1	1	3	21	30	31	0	25	114
Overall success rate	25 %	11 %	14 %	60 %	**47 %**	**45 %**	**67 %**	0 %	**29 %**	41 %

stating stakeholder consultations play a large role in this “local success” (reduction of poverty, etc.). In the absence of national stakeholder procedures, sustainable developments were shown to decrease (Benites-Lazaro and Mello-Théry, 2019).

Fig. 4 shows how each score contributed to the total score per project, categorized by subregion. It can be seen that the vast majority of projects scored within the Specific CER Cost Score (yellow bars in Fig. 4). The other two scores are less dominant (blue and green bars in Fig. 4). This again indicates that the costs were not the limiting factor for the success of most of the projects. This seems particularly true for projects in LAC, where there is a considerable number of projects which reach the defined success threshold of ≥0.6 with only scoring in two scores (PP_{quo} and $CER_{\$}$). This indicates that more projects in LAC have been cost-effective compared to projects in the other regions. In contrast, projects in Asia Mainland appear to score higher by trend within the project Performance Score (blue bars in Fig. 4) compared to the other regions. Thus, a higher share of design CER output was actually issued in Asia Mainland (on average 36 % compared to 28 % and 29 % in LAC and SEA, respectively – see Fig. 2).

3.3.2. *Effect of project size*

The total project scores depending on size classification are presented in Fig. 5 and Table 4. 175 projects (62.5 %) are classified as large in scope and 105 projects (37.5 %) are classified as small in scope, from which 49 % and 28 % are determined as “successful”, respectively (Table 4). Amongst the projects classified as “Most Successful” and “Successful” 72 % and 76 %, respectively, were large in scope. The share of large projects within the categories “Operational”, “Marginally Operational” and “Inoperative/Ineffectual” falls below 60 % and thus, the share of small projects increases within these categories which lowers success.

The higher overall success rate of large projects can also be seen from Fig. 5. At the same time, Fig. 6 shows that most of these projects are within the project subtype “Manure” and thus focused on the improvement of waste management from commercial livestock, primarily via methane capture and combustion (Warnecke et al., 2017; UNFCCC, 2025). Large manure projects experienced a baseline of success even in the absence of expected CER issuances (i.e., low PPquo). This indicates that to implement said projects, the baseline of expense for both CAPEX and OPEX is likely low. It also indicates that there is a high potential for revenue generation from issued CERs if the PPquo were to be improved upon.

According to this grading model and its success threshold of 0.6, projects classified as “large” were 1.8 times more likely to be evaluated as successful as projects classified as “small”. The results confirm that large-scale projects contribute more to GHG reductions as found by Hultman et al. (2009), but the economic factor still is the factor contributing the most to the score of large-scale projects. This might be due to the economies of scale concept or a “risk diversification effect”, which lead to proportionate cost-effectiveness and higher degrees of complexity, respectively, when the scope of a project or system increases (Sutton, 2015; Schmitt et al., 2015). For the latter, the increased complexity prevents against overarching system failure.

3.3.3. *Effect of project subtype*

Fig. 6 and Table 5 show the total project scores based on project subtype. According to this grading model and its success threshold of 0.6, landfill flaring and landfill power projects were likely to be successful almost half the time. Their success rates were comparable, and this might be explained by the similar nature of the project types. By contrast, waste water projects were likely to be successful almost a third of the time. Depending on the level of technology, this might be explained by high maintenance and staff costs, especially associated with pumping systems and wastewater treatment plants. The requirement of well-trained, highly motivated staff might also play a role.

In sharp contrast, projects dealing with the management of manure were likely to succeed 2/3 of the time. This comparatively high success rate might be explained by lower levels of technology required to reduce methane emissions from livestock manure, than say for landfill power generation, or wastewater treatment. However, within successful projects dealing with manure (31 projects), the majority were classified as “Successful” (84 %) and only 16 % were classified as “Most Successful”. The majority of successful manure projects did not achieve more than 0.6 and did not score within the transition score (see Fig. 6). Thus, the longevity or durability of successful manure projects seems to be lower than for successful projects of other types. The share of “Most Successful” projects within successful (≥0.6) landfill flaring and landfill power was higher compared to manure projects (38 % and 57 %, respectively).

Thus, the project subtype manure seems to play a role in the general success of projects, whereas landfill flaring and landfill power projects appear to represent the most successful projects. This could also be concluded from the fact that 58 % of the “Most successful” projects (25 of 43 total) are dealing with landfill flaring and landfill power. Moreover, of the 112 combined total of landfill flaring and landfill power projects in the sample, 103 of them (92 %) were classified as large. Ultimately, these 103 projects accounted for approximately 73 % of the total issued CERs in the sample (~85M of ~117M), indicating that these two factors (i.e., large projects and landfill flaring/power project subtypes) are likely the most decisive.

When looking at the project subtypes dealing with energy from waste and composting (“Biomass energy”, “Combustion of MSW”, “Composting” and “Landfill composting”) combined (29 projects in total), these projects show an overall success rate of only 24 % (7 of 29 projects). Even if only a few projects of these subtypes are within the sample size, it can be seen from Fig. 6 that “Biomass energy” projects appear to score well within the economic criteria, but less within the other two criteria (only one project scored within the transition score which is the only “successful” project within “Biomass energy” in this sample). This is different to, for example, the subtypes “Combustion of MSW” and “Landfill Composting”, where the Project Performance and Transition score appear to contribute more to the total aggregate score. Thus, these types of projects might be connected with a higher financial risk, but might have a higher CER output and higher chance to continue in the future. What is noticeable for “Composting” projects is, that apart from one being labeled as “Most successful”, all others (six projects) perform poorly in all criteria within this scoring method. Thus, considering these basic particularities, it seems worthwhile to examine individual project reports to draw conclusions regarding success stories or major shortcomings.

Mori-Clement, 2019 showed specifically, that when certain types of projects are more capital intensive than labor intensive, then the local economic benefit (e.g., via local employment) of the project decreases. However, many projects in the waste sector were shown to be more labor intensive, compared to, for example, hydro projects (Mori-Clement, 2019). Therefore, it would be vital to assess to what extent successful projects under this model are successful in other areas and expand upon the definition of success with those layers incorporated.

Note that for all three figures in the results section (Figs. 4–6), all but six “successful” projects without a transition score represent projects that were assessed only by the other two criteria as they did not qualify to receive a transition score.

4. Conclusions

4.1. Results-based conclusions

- **Project performance was consistently below expectations.**
  Only **35 %** of the expected CER volume was issued across 428 projects, with just **5.1 %** reaching or exceeding their design output. Under-delivery of CERs remains a central limitation of CDM projects in the waste sector.
- **Cost-effectiveness was not the primary barrier to success.**
  A majority (56.8 %) of projects generated CERs at $\leq$ \$30/CER, and these accounted for almost all (90.6 %) of all issued CERs. This shows that **waste-sector mitigation can be highly cost-effective**, even when performance or continuity is lacking.
- **Long-term project continuity was limited.**
  Only **27 %** of projects transitioned to the PACM or voluntary carbon markets, despite 151 projects being eligible. This suggests structural or institutional constraints on project longevity.
- **Overall success was modest: 40.7 % of projects met the success threshold.**
  Success was strongly associated with **size** and **project subtype.** Large projects were 1.8 times more likely to succeed, and the most successful categories were **landfill flaring**, **landfill power**, and **manure management.**
- **Geographic patterns were pronounced.**
  Projects in LAC and SSA achieved the highest success rates, largely due to high representation of the most successful project types and larger project scales.

4.2. Methodological conclusions

- **The scoring method proved effective for large-scale comparative assessment.**
  The equal-weighted three-criterion model enabled transparent, reproducible project ranking across a large dataset without reviewing individual PDDs. This demonstrates the utility of systematic scoring tools for assessing legacy carbon-crediting mechanisms.
- **The method is adaptable to other CDM sectors and future crediting mechanisms.**
  Because it relies on standardized, widely reported metrics (CERs, cost proxies, transition status), the approach can be applied beyond waste management—offering a baseline methodology for evaluating the performance of carbon credit portfolios.
- **A development-impact dimension should be incorporated in future models.**
  While this study focused on environmental and economic criteria, future scoring systems would benefit from explicitly integrating social and local co-benefits, possibly aligning with UNFCCC sustainable development indicators or UNFC-style codification.
- **Data gaps remain a limiting factor.**
  Approximately 71 % of registered projects lacked sufficient data for full evaluation. Future frameworks should require more consistent financial and operational reporting to enable more robust longitudinal analysis.

4.3. Future scope

As stated in the results and discussion section, a critical next step would be to link these results with additional indicators—specifically related to sustainable development and technology transfer—that further refine and anchor their relevance for practical application. Given the ability of this model to identify and categorize the degree of success of large swaths of projects efficiently, the results will be used to identify unusually unsuccessful and exceptionally successful projects as case studies for further study, with the intent to pin down the underlying factors of their success or lack thereof. These results will hopefully be used to shape future policy and frameworks for future project implementation under the PACM or the voluntary carbon market.

CRediT authorship contribution statement

Richard David Lee: Writing – original draft, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Therese Schwarzböck:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Sara Neuburg:** Writing – review & editing. **Francis Okori:** Writing – review & editing. **Johann Fellner:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2025.101389.

Data availability

Data will be made available on request.

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