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Techno-economic and environmental assessment of methane oxidation layer measures through small-scale clean development mechanism – The case of the Seychelles

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ABSTRACT

Unclosed coastal landfills in small island developing states are major sources of greenhouse gases and other environmental impacts. This is a major problem for sustainable waste management systems mainly due to the lack of economic resources. The clean development mechanism (CDM) appears as a possibility to facilitate sustainable financing. Implementing a methane oxidation layer (MOL) emerges as a feasible technical option for this kind of small landfills since landfill gas extraction is usually not viable. This paper presents a techno-economic and environmental assessment of MOL implementation in the Providence landfill (Seychelles) as a small-scale CDM measure. Results show that the MOL measure could avoid by 2030 between 94 and 20 kt CO_2 eq. Concerning profitability, results clearly show that it depends on the existence of stabilized biomass material within the island. Thus, the MOL measure starts to be profitable in some scenarios for certified emission reductions (CER) prices higher than 26 €/t CO_2 eq. that seem possible depending on the emissions' market development. When not profitable under CDM, the MOL measure might be used to reduce CO_2 emissions from the domestic climate effort under the Paris Agreement since the unitary abatement costs is between 10 and 423 €/t CO_2 eq. Moreover, the MOL measure contributes to the sustainable development goals (SDG) achievement – mainly SDG8, SDG13, and SDG14. Finally, results call for a prompt action in Seychelles since the sooner the MOL is implemented after the landfill is closed, the more profitable.

1. Introduction

Increasing waste generation, climate change and marine litter are very important (and interconnected) environmental issues nowadays for most countries in the world. Those are particularly critical in small island developing states (SIDS) mainly due to economic growth, limited land availability, lack of economic resources and knowledge to address waste issues (Mohee et al., 2015), as well as high touristic pressure (Meylan et al., 2018).

According to the United Nations Environment Programme (UNEP, 2019), SIDS' waste primarily ends up in either dumpsites or the marine environment. Landfills, usually uncontrolled or illegal, are the first choice to finally dispose wastes due to the lower cost and lower technical requirements comparing to other "cleaner" technologies (e.g. anaerobic digestion or incineration). Moreover, the implementation of these "cleaner" technologies without proper planning can lead to environmental and economic failure, and in some cases, the characteristics and composition of wastes do not allow the use of other techniques such as incineration (Margallo et al., 2019).

The waste stream entering the landfills in SIDS contain a high percentage of organic wastes, around 41–48% (Mohee et al., 2015). This biodegradable waste is a major source of methane (CH_4) emissions, a greenhouse gas (GHG) many times more potent than carbon dioxide (CO_2) with high contribution to the climate change impact. Landfill CH_4 contributes approximately 11–12% of the global anthropogenic CH_4 emissions (Ritzkowski and Stegmann, 2010).

It is common that landfills in SIDS reach their capacity and stop receiving wastes without a proper closure and maintenance,

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allowing more CH_4 emissions to reach the atmosphere. Due to the pressing and major challenge in sustainable waste management (SWM), policy-makers have the will to implement potential solutions to this waste management issue, but the lack of economic resources and the lack of understanding of current SWM practices hinder their efforts. Possible solutions might come through the different flexible mechanisms allowed by the United Nations Framework Convention on Climate Change (UNFCCC) in order to achieve the reduction targets for GHG emissions established by the Kyoto Protocol, such as the clean development mechanism (CDM). The CDM allows industrialised countries and countries in transition to generate emission credits (called certified emission reductions – CERs) through investment in emission reductions projects in countries without emission targets.

The main activities to manage CH_4 emissions at landfills are the implementation of active landfill gas (LFG) extraction systems and the CH_4 emission avoidance through oxidation (Bogner et al., 2007). The former requires certain criteria concerning the quantity of wastes entering the landfill and the structure of the landfill (UN, 2007a) that most of the times are not met by small landfills in SIDS. Greiner (2004) set a threshold size of 10 Mio. tonnes of waste put in place at the closure of the landfill to consider an LFG-CDM project commercially attractive. Besides, methane concentration and volume flux are usually too low for energy recovery or flaring. On the other hand, the CH_4 oxidation through biocovers or methane oxidation layers (MOL) might be a more feasible option for this kind of small landfills (Abichou, 2020).

The MOL is a landfill cover system that consists of methane oxidising material (MOM) derived from stabilized biomass (SB) or compost that contains methanotrophic bacteria. These bacteria are able to oxidise the emitted CH_4 from decay processes in the disposed waste into CO_2 (Stern et al., 2007). The efficiency of the MOL depends on the quality and biochemical relevance of the cover material (Fricke and Kölsch, 2009). Sadasivam and Reddy (2014) conducted a review summarizing previous laboratory and field-scale studies, as well as the issues and challenges in developing effective and economical bio-based cover systems. The MOL measure consists of two major steps: the acquisition of required cover material with appropriate properties (both MOM and soil/construction material for the gas distribution layer), and the construction of the MOL as landfill cover (both landfill surface shaping and the placement of the MOL layers). Scheutz et al. (2014) carried out a field-scale study in Denmark of a bio-cover system including an economic analysis that showed the competitiveness of this technology comparing to other existing GHGs mitigation options.

According to the Decision 1/CMP.2 of the Kyoto Protocol (UN, 2007b), CDM activities related to waste handling and disposal that achieve certain threshold criteria (i.e. those that result in emission reductions of less than or equal to 60 kt CO_2 eq. annually) are defined as small-scale projects. The size of the project is meaningful for the economic feasibility within the CDM since it is related to a significant degree on transaction costs and institutional barriers in the host countries (Michaelowa and Jotzo, 2005).

A literature review shows that the majority of CDM investments flows into large-scale projects and so small-scale projects are overlooked for carbon finance (Mariyappan et al., 2005). Furthermore, there is an uneven geographic distribution of CDM projects. As shown by Qui (2018), SIDS and other least developed countries (LDC) are crowded out since 85% of the issued CERs are from China, India and Brazil. In line with these two facts, literature addressing waste management CDM projects in developing countries practically ignore small-scale projects and MOL since it is mostly focused on large-scale projects and LFG. Thus, Bufoni et al. (2015) analysed the financial attractiveness of 431 large waste management projects around the world concluding that LFG is the most implemented solution but with serious doubts about its economic efficiency. El-Fadel et al. (2012) analysed the economic viability of several LFG recovery and power generation schemes in Lebanon concluding that the viability of these kind of projects in developing countries is doubtful. In the same line, Couth et al., (2011) assessed the viability of LFG to electricity CDM projects in Africa and concluded that small to medium sized LFG CDM projects are not viable in Africa unless either there is a renewable energy feed-in-tariff or flared is used instead of power generation. Concerning methodological issues to analyse the profitability of CDM projects, Schneider et al. (2010) proposed a methodology for a systematic assessment of CDM projects' financial and environmental performance using a net present value (NPV) based indicator. Flamos et al. (2005) developed a web-based tool for the assessment of projects' financial feasibility set by the CDM modalities.

The research gap on small-scale waste management CDM projects, and especially on MOL, is evident although small-scale projects are of a higher quality in terms of their contribution to sustainable development since they integrate better in the local economy (Olsen and Fenhann, 2008). According to Couth and Trois (2012) the CERs produced by small-scale projects should have a higher value generating more income. Therefore, it is important to analyse and foster CDM projects in SIDS and LDC that allows them to cost-effectively solve local environmental problems attracting foreign investments. Thus, the main aim of this paper, and in the end its novelty, is to conduct an initial techno-economic and environmental assessment of potential small-scale CDM activities of CH_4 avoidance through the implementation of a MOL in the specific context of a SIDS: the Seychelles. The present study intends to analyse the variables that ultimately might drive or hinder investments in this kind of projects, such as the global price of CERs or the material's price, and their values for possible economic feasibility.

This paper is organised as follows. Section 2 presents the methodological approach followed to calculate both the emission reductions and the financial indicator, as well as highlight other important aspects to consider. Section 3 introduces the background information and context of the Seychelles case study, as well as the specific data needed for the assessment. Section 4 provides the results and those are discussed accordingly. Limitations for the analysis are posed in Section 5. Finally, Section 6 presents the concluding remarks.

2. Materials and methods

In order to assess the MOL measure under the CDM, different aspects are studied as shown in Fig. 1. First, the environmental performance is measured through the calculation of the emissions reduction achieved with the measure. Secondly, the financial performance is calculated through the NPV. Finally, other important aspects need to be considered under CDM such as applicability criteria, additionality, and the sustainable development goals' achievement.

2.1. Environmental performance

In order to estimate the emission reductions, the method provided in the methodology AMS-III.AX./Version 1 is used (UNFCCC, 2011a). As shown in Fig. 2, the emission reductions achieved by the project activity in each year y (ER_y) can be calculated according to Eq. 1 as the difference between the baseline emissions (BE_y) and the sum of project emissions (PE_y) plus leakage (LE_y), all measured in t CO_2 eq. Note that the baseline scenario of the measure is the continuation of the current situation (i.e. the landfill site is emitting CH_4 to the atmosphere) since there are no legal regulations

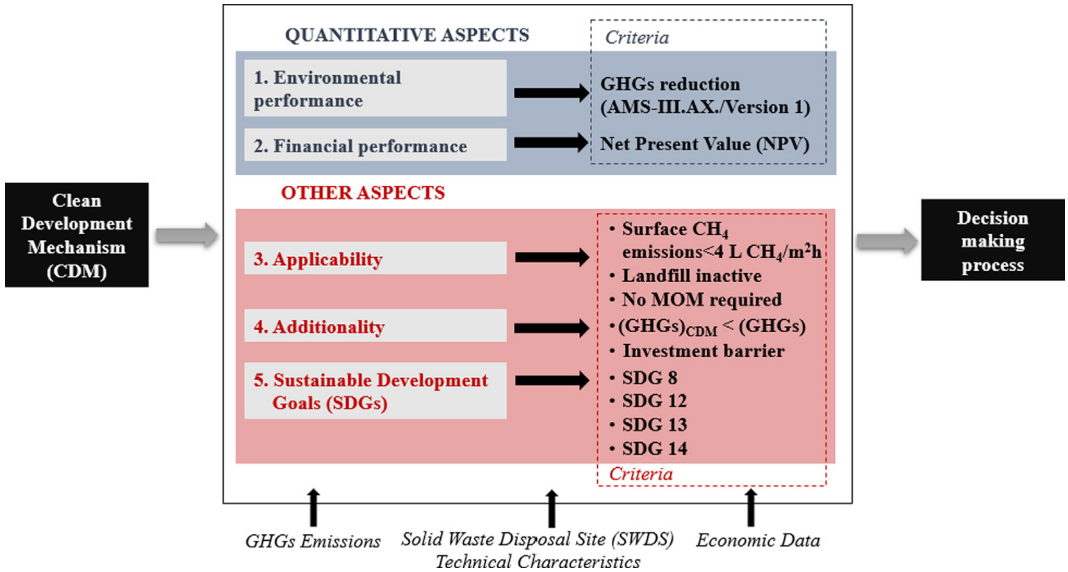

Fig. 1. Methodological approach to assess the MOL measure under the CDM.

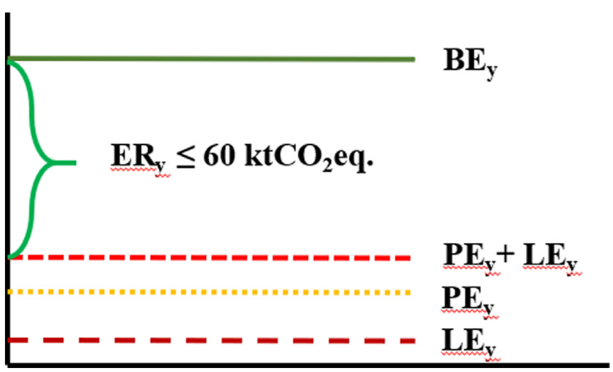

Fig. 2. Emission reduction calculation methodology.

enforcing the engineered covering of the landfill site once it reaches its full capacity.

$$ER_y = BE_y - (PE_y + LE_y) \quad (1)$$

The baseline emissions are calculated *ex-ante*, i.e. before the project is implemented, as shown in Eq. 2:

$$BE_y = BE_{CH4,SWDS,y} * Af_{MOL,y} \quad (2)$$

where $BE_{CH4,SWDS,y}$ are the methane emissions from the designated solid waste disposal site (SWDS) in t CO_2 eq. in the absence of the project activity at year *y* (further details in the Supporting Material – Section 1). $Af_{MOL,y}$ is the area fraction of the SWDS (in %) that will be covered with MOL up to year *y*.

The project activity emissions consist of the sum of the emissions due to transport of the materials ($PE_{y,transp}$), the emissions from electricity or fossil fuel consumption ($PE_{y,power}$), and the residual methane emissions of the SWDS covered with MOL ($PE_{y,MOL}$), all measured in t CO_2 eq. (see Eq. (3)). More details of the calculation of each element are included in the Supporting Material – Section 2.

$$PE_y = PE_{y,transp} + PE_{y,power} + PE_{y,MOL} \quad (3)$$

Finally, for this kind of CDM the leakage (LE_y) is considered zero.

2.2. Financial performance

In order to see the financial feasibility of the CDM measure, the NPV is calculated. NPV is the difference between the present value of cash inflows and the present value of cash outflows (i.e. the net cash flow) over a period of time (see Eq. (4)).

$$NPV = \sum\nolimits_{t=0}^{T} \frac{CF_t}{(1+r)^t} \quad (4)$$

where CF_t is the net cash flow in the period *t*, *r* is the discount rate, and the number of periods go from 0 to T. It is assumed that an investment with a positive NPV will be profitable, and an investment with a negative NPV will result in a net loss. An important drawback of using an NPV analysis is that it makes assumptions about future events that may not be reliable.

In order to calculate this indicator, the CF_t is calculated by subtracting the annualized initial capital costs (feasibility study, project design preparation, equipment, land preparation, etc.) and the operational costs (MOL material acquisition and application, maintenance, monitoring, verification, etc.) from the annual revenues (from the sale of CERs in the market).

2.3. Other aspects

2.3.1. Applicability

This measure is applicable when three criteria are fulfilled: the SWDS must have a low residual surface methane emission (i.e. less than 4 L CH_4/m^2h); the landfill is no longer receiving wastes for disposal and it has no an active gas extraction system; and, no legal regulation is in place requiring the surface covering with MOM.

2.3.2. Additionality

Additionality must be demonstrated and it is defined as follows in the Decision 17/CP.7 (UN, 2001): “A CDM project activity is additional if anthropogenic emissions of GHGs by sources are reduced below those that would have occurred in the absence of the registered CDM project activity”. The emission reduction of CDM project activity is additional relative to baseline, this means that without the support of CDM, the activity has competitive disadvantage and/or obstacles (such as technology, financing, risk and human resources), that are difficult to overcome with domestic conditions (Yunna and Quanzhi, 2011). On the contrary, if a project would have been implemented in normal commercial operation in the absence of the CDM incentives, the emission reductions would have occurred anyway and no additional emission reduction could be claimed (Öko-Institut, 2016). Four main criterions can be used to demonstrate additionality: the investment barrier, the technology barrier, the habit disorder, and other barriers (political, institutional, information and resource).

2.3.3. Achievement of sustainable development goals (SDGs)

One of the particular aims of the CDM is to assist the host country in achieving sustainable development by promoting environmentally friendly investment. Sometimes this aim is marginalized partly due to the difficulties surrounding the definition and the measurement of sustainability, especially in developing countries (Hugé et al., 2009).

3. Case study – The Seychelles

The Republic of Seychelles is a SIDS composed of 115 islands located northeast of Madagascar in the Indian Ocean in the AIMS region (Atlantic, Indian Ocean, Mediterranean and South China). It has approximately 94,700 inhabitants, being Mahé the biggest and most populated island and the location of the capital city Victoria (see Fig. 3).

The main way of disposing municipal solid waste and other fractions in Mahé is at the designated SWDS in Providence. Except for PET bottles, large scrap metal and aluminium cans, almost all of the waste generated by the residential and business sectors goes to landfilling (Talma and Martin, 2013). The Providence landfill (PL) site consists of two sections (see Fig. 3): Landfill N°1 (PL1) operating since 1995, and landfill N°2 (PL2) operating since 2016.

There is no much technical data available on PL1. According to Nippon Koei (2019) the site has an area of around 65,000 m^2, it is unlined, there are no leachate or landfill gas control systems in place and minimal environmental control is undertaken. Although there was no general filling plan used, a general sequence of filling was established. For some time, waste has been deposited in layers in defined areas, compacted and covered with inert material on completion of each main filling phase (Scott Wilson, 2004). PL1 virtually reached its full capacity in 2015 (Lai et al., 2016) and the waste disposal activities have been recorded since 1999 (landfill management was given to the private company STAR Seychelles in 1997) at varying rates as shown in Table 1. The site is not fully closed since the Ministry still allows the operator to dispose liquid waste (Nippon Koei, 2019).

PL2 started operation in 2016 and has been designed as a sanitary landfill since it is lined with a composite plastic material to prevent leaching (Lai et al., 2016), and it is engineered so as to extract the methane for electricity production (Talma and Martin, 2013) even if LFG is not vented and the leachate plant is not operating nowadays. According to Nippon Koei (2019) it has a land area of around 79,000 m^2, divided in two disposal units: PL2-1 (35,100 m^2) and PL2-2 (43,900 m^2). Only PL2-1 is active (PL2-2 is still in preparation) and depending on the forecasted waste generation amounts, it is projected to reach its full capacity by 2022 (only PL2-1), or by 2025 (PL2-1 + PL2-2) (Nippon Koei, 2019). Table 1 shows the yearly waste amounts and the future projections.

The composition of the different fractions, based on different sorting analysis done at the weighbridge of PL2, has been reported by Kannengießer and Schebek (2017) as shown in Table 2. The average composition is considered for all previous periods as a conservative assumption.

This case study assumes that at the projected waste generation rates mentioned before, the PL2 will also reach its capacity by 2025 and most probably, similarly to PL1, it will be poorly controlled without a final coverage generating massive CH_4 emissions. It is considered that covering PL1 and PL2 are two independent actions since the starting date for PL1 would be 2021, and for PL2 it would be 2026 when full.

3.1. Scenario variables and scenario definition

In order to analyse the techno-economic and environmental performance of covering PL1 and PL2 with a MOL, and facilitate the decision-making process, different scenarios are proposed combining three decision variables:

1. the number of years to complete the MOL application (T_{AfMOL}) - the MOL application is planned along several years due to the large extension of the PL site (i.e. PL1 = 65,000 m^2 and PL2 = 79,000 m^2), and thus, the possible constraint in the availability of SB. Each year a % of the PL area denoted as $Af_{MOL,y}$ (see Eq. 2) is covered, that equals to 100/T_{AfMOL}. In this paper, T_{AfMOL} is a discrete variable and will take the values of 7, 10, 14 or 21 years;
2. the crediting period (CP) - CDM projects can receive CERs only for a defined period of time. Thus, the project operator must choose between two different approaches concerning the length of the CP: either a maximum of 7 years, which may be renewed at most 2 times (i.e. a total of 14 or 21 years), or a maximum of 10 years with no option of renewal. In this paper, all possible values are assessed (i.e. 7, 10, 14, and 21 years);
3. the place of origin of the SB material – in this study this variable can take two values: either imported (Imp) or local (Sey). The former considers that Seychelles has no capacity to produce the SB in the estimated needed quantities, and those are imported from South Africa that is the biggest supply market for these kind of products (Trademap, 2020). The latter, considers that the SB is produced in Seychelles since nearby the PL there is a composting plant, albeit it is not operating (Kannengießer and Schebek, 2017). The plant was opened in 2,000 and it has a capacity of about 3,000 tonnes of compost per year (Scott, Wilson, 2004). It was producing only about 1,000 tonnes of compost per year and there were difficulties in finding a market since the price of the compost was considered to be too expensive and inhibited sales. The plant was phased out allegedly for lack of profitability (Gonzalves, 2017). Note that this situation assumes the capacity expansion and re-opening of the existing composting plant that would not be included in the boundaries of the MOL measure and so, neither the emission reductions nor the costs/benefits derived from that activity would be accounted for.

Thus, the combination of the all possible values for the three variables (i.e. 7, 10, 14 and 21 for T_{AfMOL}; 7, 10, 14 and 21 for CP; and Imp or Sey for SB) leads to 32 scenarios for PL1 and 32 scenarios for PL2. It is important to highlight that results from scenarios of PL1 and PL2 are not comparable between them since those are independent actions and not equivalent.

3.2. Economic feasibility data

3.2.1. Capital expenditure (CAPEX)

The MOL is a technology for climate mitigation that requires small investments comparing to other technologies such as CH_4 flares. First, a feasibility study and a project design preparation are needed, calculated as a fixed cost of 28,000 € (Scheutz et al., 2014). CAPEX also includes the initial landfill's surface shaping to prepare for the MOL, estimated multiplying a unitary cost of around 0.8 €/m^2 (that includes the rental of the machinery and

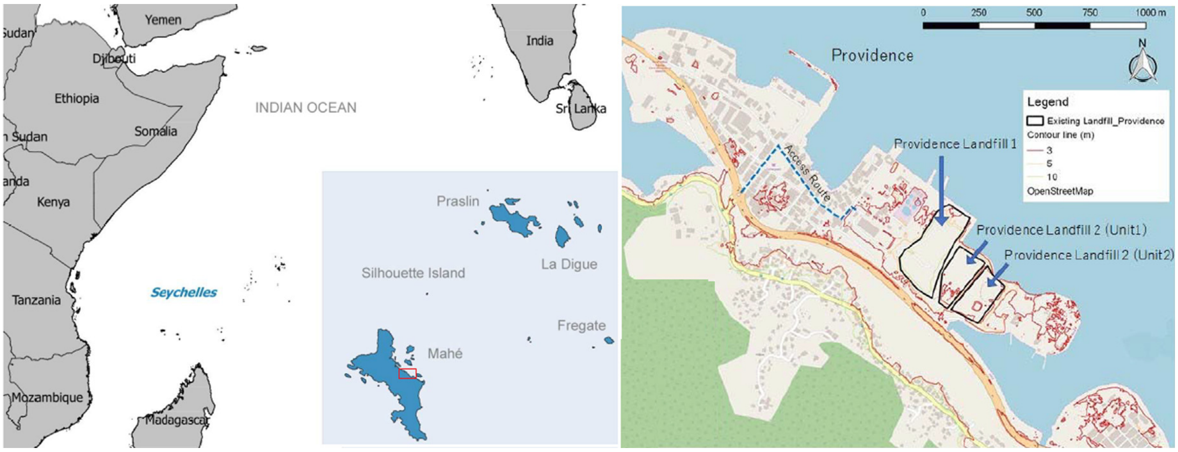

Fig. 3. Geographical location of Seychelles (Kannengießer and Schebek, 2017) with the detailed location map of Providence landfill Site in Mahé (Nippon Koei, 2019).

Table 1
Total waste amount to Providence Landfill in tonnes. Source: Kannengießer and Schebek (2017).

PL1						PL2		
Year	Annual waste flow t/year	Aggregated waste flow t	Year	Annual waste flow t/year	Aggregated waste flow t	Year	Annual waste flow t/year	Aggregated waste flow t
1995	30775[a]	30,775	2006	49,041	465,312	2016	73,225	73,225
1996	30775[a]	61,550	2007	53,854	519,166	2017	77925[b]	151,150
1997	30775[a]	92,325	2008	48,896	568,062	2018	81482[c]	232,632
1998	30775[a]	123,100	2009	49,447	617,509	2019	83249[c]	315,882
1999	30775[a]	153,875	2010	75,539	693,048	2020	84430[c]	400,312
2000	42,636	196,511	2011	66,866	759,914	2021	89350[c]	489,662
2001	41,787	238,298	2012	62,258	822,172	2022	93680[c]	583,342
2002	43,404	281,702	2013	75,533	897,705	2023	97550[c]	680,892
2003	48,839	330,541	2014	79,226	976,931	2024	101057[c]	781,949
2004	40,842	371,383	2015	72,319	1,049,250	2025	104276[c]	886,225
2005	44,888	416,271						

[a] since there is no record of these data, the same value as the first recorded year (i.e. 1999) is considered.
[b] Data for 2017 have been projected by Kannengießer and Schebek (2017) based on extrapolation of direct measurement at the PL-2.
[c] Data for 2018 and subsequent periods have been projected as proposed by Lai et al., (2016) using a landfill rate model (based on population (data from UN) and GDP per capita projections (i.e. medium scenario)).

Table 2
Waste composition expected per waste type for 2016 and 2017. Note that this composition is extrapolated from Class 1, 2 and 5 at the weighbridge in PL2.

Waste type *j* (%)	2017	2016	Average
Wood and wood products	14.9	2.7	8.8
Pulp, paper and cardboard	20.6	15.1	17.8
Food, food waste, beverages and tobacco	13.8	31.7	22.8
Textiles	3.2	5.8	4.5
Garden, yard and park waste	6.5	10.3	8.4
Glass, plastic, metal, other iner waste	41	34.4	37.7
TOTAL	100	100	100

the fuel) by the area of the PL depending on the scenario. Further information on the detailed calculations are on the Supporting Material – Section 3. Besides, when not available in place, it is also required an initial investment on a vehicle to properly implement the MOL, around 65,000 € (AGFACTS, 2020). In addition to the costs incurred by the project, certain specific costs are associated with the various stages of the CDM project cycle (UNEP, 2007a), including the planning phase, the initial feasibility study, the project design document, and the validation and registration fees. For this case study, 40,000 € are considered since for small-scale projects a range between 15,700 € and 57,000 € is given (a conversion rate of 0.85 €/$ is used).

3.2.2. Operation expenditure (OPEX)

The operational costs of the MOL are calculated annually and include labour costs, fuel and energy for the operation activities, acquisition of materials for the MOL (including transport), monitoring and maintenance activities, as well as CDM project cycle costs.

Labour costs only accounts for the personnel employed during the implementation of the MOL. The operational labour costs are calculated multiplying the number of workers needed by their annual salary. Further information on the detailed calculations are on the Supporting Material – Section 4.1.

Operational costs for the fuel consumed in the activities include: The fuel used in the truck that transports both the SB and the gas distribution layer material to the landfill (considering only the transport within Seychelles), the fuel consumed by the machinery spreading them over the landfill, as well as the energy to transform the SB into MOM (i.e. screening, blending and maturation). According to literature (UNFCCC, 2011b), in order to cover 1 m^2 of the landfill with an effective MOL, a layer of a minimum thickness of 2 m of MOM is needed[1], as well as 0.4 m of distribution material to be placed bellow the MOM. Further information on the detailed calculations are on the Supporting Material – Section 4.2.

[1] with specific characteristics concerning Total Organic Carbon (greater than4% dry mass), Respiration activity (≤8 mgO_2/g dry matter), and ammonium concentration (less than 350 ppm dry matter and no detectable nitrite

For the acquisition of the MOL materials, it is considered that the distribution material can be obtained within the country at a market price of 11 €/t (CCC, 2020) (a conversion rate of 0.047 €/SCR[2] is used). but the MOM depends on the scenario. For SBImp scenarios where MOM is imported from South Africa, the price of 389 €/t intended as CIF[3] is used (Trademap, 2020). On the other hand, for SBSey scenarios where MOM is produced in the composting plant at PL, the price of 25 €/t is considered since it is the last existing reference according to Scott Wilson (2004).

Monitoring activities are based on Pivato et al. (2018) and the annual unitary cost used for this study is 0.29 €/m^2. The maintenance costs includes the addition of new compost and reparison of introduced hot spot areas as explained in Scheutz et al. (2014) and an annual unitary cost of 0.1 €/m^2 is used. Finally, concerning the CDM project cycle costs, UNEP (2007a) estimates a minimum of 5,000 € per year +2% of the CERs validated each year.

3.2.3. Revenues

In this kind of projects, CERs revenues are the only positive income for the cashflow. Revenues are calculated as the quantity of CERs obtained per year multiplied by their value on the market.

4. Results and discussion

Results are shown and discussed for the different scenarios of PL1 and PL2 depending on, as explained before, the number of years to complete the MOL application (T_{AfMOL}), the crediting period option (CP), and the SB origin (SB).

4.1. Environmental performance

First of all, the environmental performance results that quantify the total emissions avoided (kt CO_2 eq.) by the MOL measures (i.e. $\sum_y ER_y$) are shown in Table 3.

Results show that covering the landfill in the shortest time possible will render higher emissions reduction within a selected CP. In the hypothetical case in which the PL could be covered in one year (i.e. T_{AfMOL} = 1), unlikely since the required quantities of SB for one year seem excessive, the total emissions avoided will range between 112 and 228 kt CO_2 eq. for PL1, and between 200 and 367 kt CO_2 eq. for PL2.

Besides, Table 3 also shows that the influence of the SB origin is almost negligible in the total environmental performance results since the only difference between SBImp and SBSey is due to the emissions of transporting the SB by barge from South Africa. Even if the reduction in the transport emissions for the SBSey comparing to SBImp equals 95%, those represent less than 2% of the total environmental performance.

According to the intended nationally determined contribution (INDC) submission to the Paris Agreement (UNFCCC, 2015), Seychelles pledged to reduce GHGs by 122.5 kt CO_2 eq. in 2025 and by 188 kt CO_2 eq. in 2030, both below "business as usual" levels. In that document, a flaring project at PL1 was identified that would reduce emissions by 13.91 kt CO_2 eq. by 2030[4], but up to date it never materialized. According to the results obtained in this paper, the MOL measure could reduce by 2030, depending on the PL in which it is applied and the T_{AfMOL}, between 94 and 34 kt CO_2 eq. for PL1 (i.e. 50% and 18% of the INDC reductions), and between 62 and 20 kt CO_2 eq. for PL2 (i.e. 33% and 11% of the INDC reductions).

4.2. Financial performance

For the profitability results, the origin (and consequently the price) of the SB material clearly plays a key role, but is not the only determining variable. The CER prices will determine the profitability of the measure, but these might not depend on the project owner (as explained below). Fig. 4 shows the NPV results (measured in thousand €) depending on the CER prices (measured in €/t CO_2 eq.) for SBSey scenarios (detailed results on the Supporting Material – Section 5). SBImp scenarios are not shown in Fig. 4 since the MOL measure is never profitable when CER prices are lower than 50 €/t CO_2 eq. (selected as the maximum reasonable market price as discussed below in this section). Thus, for PL1-SBSey, the MOL measure would never be profitable for CER prices below 30 €/t CO_2 eq. For CER prices of around 40 €/t CO_2 eq. three scenarios appear as profitable i.e. T_{AfMOL}7-CP14 and 21, and T_{AfMOL}10-CP21. Finally, for CER prices of 50 €/t CO_2 eq., apart from the three scenarios already profitable, other five scenarios appear as profitable: T_{AfMOL}21-CP21, T_{AfMOL}14-CP21 and 14, T_{AfMOL}10-CP14 and T_{AfMOL}7-CP10.

Concerning PL2-SBSey, Fig. 4 shows that already at a CER price of 30 €/t CO_2 eq. three scenarios appear as profitable: T_{AfMOL}7-CP14 and 21, and T_{AfMOL}10-CP21. For CER prices of 40 €/t CO_2 eq., apart from the three scenarios already profitable, other six scenarios appear as profitable: T_{AfMOL}7-CP10, T_{AfMOL}10-CP10 and 14, T_{AfMOL}14-CP14 and 21, and T_{AfMOL}21-CP14 and 21. Finally, all scenarios are profitable for CER prices of 50 €/t CO_2 eq. except for T_{AfMOL}21-CP7. It is important to note that some scenarios of PL2 are profitable even when the full landfill is not covered at the end of the CP denoted in Fig. 4 as yellow shaded (e.g. T_{AfMOL}10-CP7 for CER prices of 50€/t CO_2 eq., T_{AfMOL}21-CP14 for CER prices of 40€/t CO_2 eq.).

Those prices of CER that render the MOL measure profitable might seem unrealistic comparing to the actual CER price in the market (i.e. 0.30 €/t CO_2 eq. by July 2020 according to SendeCO_2[5]). However, it can be a future possible value depending on the development of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) established under the International Civil Aviation Organization (ICAO) that aims to achieve the global aspirational goal of carbon–neutral growth of international civil aviation from 2020 onwards (average baseline emissions of 2019 and 2020). Under CORSIA, airlines will be a significant source of demand for carbon credits after 2020, and ICAO included CDM as one of the 6 selected eligible programmes to provide carbon credits. ICAO also defined certain quality criteria in order to ensure the environmental integrity of the scheme, and yet CDM has to overcome certain shortcomings in their procedure to assure them (i.e. concerning additionality criteria, the sustainable development criteria, and safeguards in place) (ICAO, 2020). Different restrictions are still under discussion that will affect the volume and cost of supplying CERs such as vintage restrictions (restriction in times of registration or project start), restrictions of specific project types or restrictions to specific host countries (DEHSt, 2018). Furthermore, there is also the possibility of offering the CERs held in the CDM registry to the general public for voluntary cancellation at any price determined by the project owner. In this way, CERs are exposed to a wider group of potential purchasers and can be bought by people and organizations to offset their own unavoidable emissions or as a contribution to the global climate action. On the voluntary markets, buyers pay vastly different prices for voluntary carbon offsets, from less than 0.43 €/t CO_2 eq. to more than 43 €/t CO_2 eq., though the average price in 2018 was 2.5 €/t CO_2 eq. (FTEM, 2019).

For the cases in which the MOL measure is not profitable as CDM, its implementation in Seychelles might be a good option in order to reduce CO_2 emissions from the domestic climate effort

[2] SCR – Seychelles Rupee
[3] Cost, Insurance and Freight
[4] considering that only 50% of the emissions are captured
[5] SendeCO2 - https://www.sendeco2.com/es/precios-co2

Table 3
Total emissions avoided (in kt CO_2 eq.) by the MOL measures for the different scenarios.

			PL1				PL2			
SBImp	T_{AfMOL}	CP	7	10	14	21	7	10	14	21
	7 years		58.8	92.7	129	175	99.3	150	202	266
	10 years		*41.2*	71.1	107	153	*69.6*	114	166	230
	14 years		*29.4*	*50.8*	82.7	129	*49.7*	*81.7*	127	191
	21 years		*19.6*	*33.9*	*55.1*	93.6	*33.2*	*54.5*	*84.9*	138
SBSey	T_{AfMOL}	CP	7	10	14	21	7	10	14	21
	7 years		59.9	93.9	130	176	101	151	203	267
	10 years		*42*	72.3	109	155	*70.5*	116	168	231
	14 years		*30*	*51.6*	83.8	130	*50.4*	*82.7*	129	192
	21 years		*20*	*34.4*	*55.9*	94.7	*33.6*	*55.1*	*85.8*	140

Note that the scenarios in which the landfill is not totally covered at the end of the CP are shown in italics (i.e. $T_{AfMOL} \leq$ CP).

under the Paris Agreement, but taking into account that both options are incompatible in order to avoid double-counting (i.e.

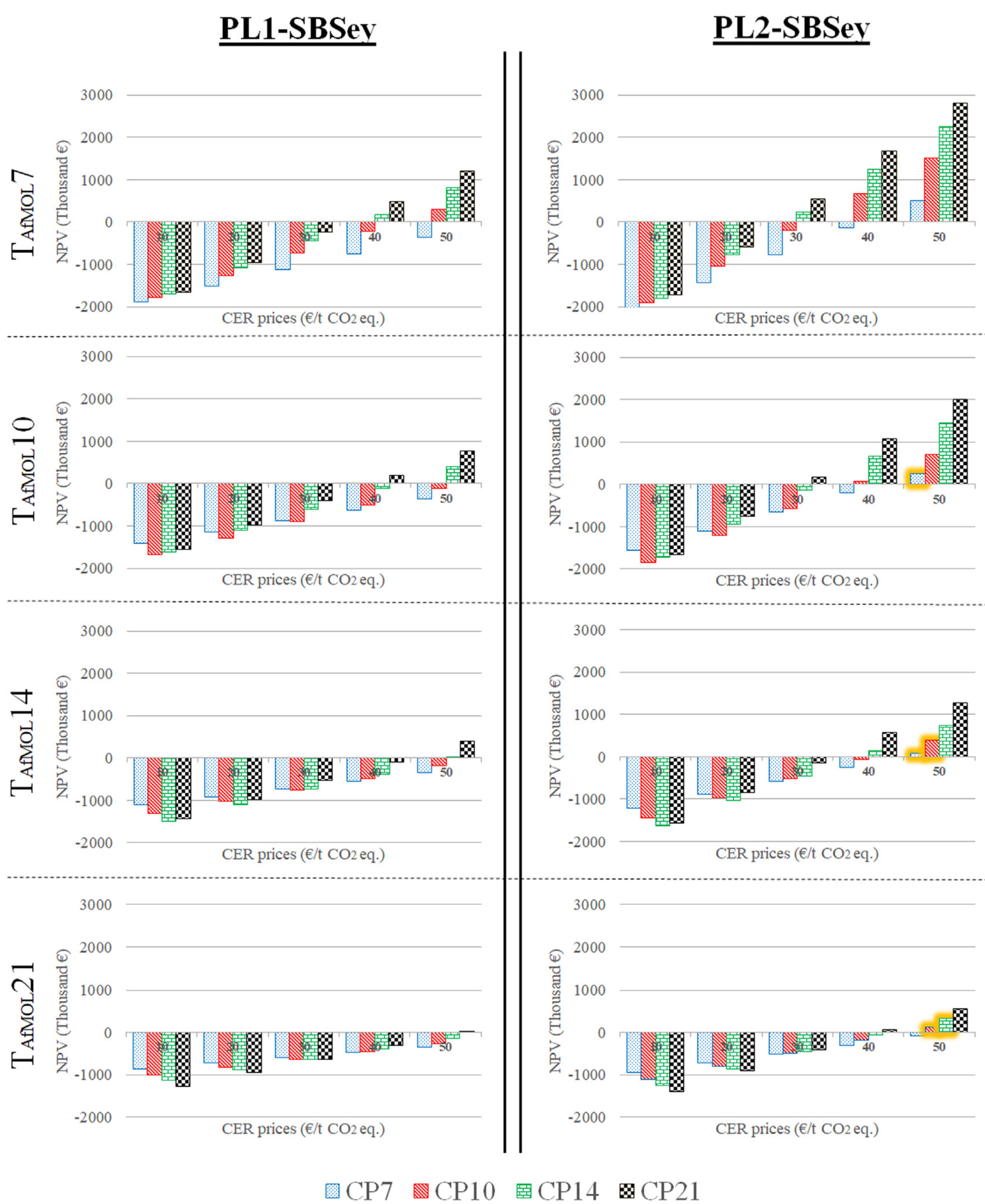

Fig. 4. Profitability assessment for SBSey scenarios showing the NPV results depending on the CER prices.

reduction units that are sold in an international market should under no circumstances also be claimed by the country where the emission reduction occurred in that case (CMW, 2019)). The INDC estimated that the cost of achieving the reduction objective in 2030 (i.e. 188 kt CO_2 eq.) would be at least 263 million € (including mitigation actions on the public electricity sector, waste management, and land transport), leading to a unitary abatement cost of 1395 €/t CO_2 eq. The flaring project at PL1 identified within the INDC and budgeted at around 17.9 million € would lead to a unitary abatement cost of 1285 €/t CO_2 eq. According to this paper, the MOL measure could achieve unitary abatement costs of around 13–46 €/t CO_2 eq. for PL1-SBSey, 10–32 €/t CO_2 eq. for PL2-SBSey, 140–423 €/t CO_2 eq. for PL1-SBImp, 112–304 €/t CO_2 eq. for PL2-SBImp.

4.3. Applicability, additionality, and sustainable development

As mentioned in the methodology section 2.3, there are other aspects to be considered within the CDM framework. For the applicability of the MOL measure, this case study fulfill all three criteria: the landfill is no longer receiving wastes and no active gas extraction system is in place, no legal regulation is in place requiring the surface covering with MOM, and the site presents residual surface methane emissions lower than 4 L CH_4/m^2h (1.89 L CH_4/m^2h for PL1 and 3.88 L CH_4/m^2h for PL2).

Concerning additionality, it is important to note that, for this kind of projects, CERs are the only sources of revenue. In these cases, attending to the investment barrier, additionality is automatic.

Finally, it is important to further analyse the contribution of the project activity to the SDGs achievement. Thus, the following SDGs benefits have been identified:

SDG 8 – Decent work and economic growth: the activity will create several direct job positions at the SWDS and several indirect job positions for compost suppliers. In the scenario in which the compost is produced in Seychelles, clearly the benefit for the host country will be higher since the market for that product will be reactivated and the composting plant might be re-opened and expanded due to a stable and profitable market. This will contribute to the target 8.5 "By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value" measured through the official indicator 8.5.2 – Unemployment rate.

SDG 13 – Climate action: the activities quantified combat climate change and its impacts though emissions reductions from oxidizing CH_4 and thus avoiding CO_2 eq. emissions to the atmosphere as shown in Table 3. This can contribute to the target 13.2 "Integrate climate change measures into national policies, strategies and planning" measured through the official indicator 13.2.2 – Total greenhouse gas emissions per year.

SDG 14 – Life below water: due to SIDS' limitation in space, landfills are placed in the proximity to oceanic waters and waterways increasing the chances of being an additional source of marine litter. Furthermore, landfills have been recognized as a major source of plastics losses to the environment through different pathways (Yadav et al., 2020). Estimations of the plastic losses from mismanaged landfills range between 5% (Kellen, 2014) and 47% (Lebreton and Andrady, 2019). Following the estimations made by Jambeck et al. (2015) mismanaged plastic waste (mainly computed as inadequately disposed) in Seychelles will account for around 5,500 tonnes by 2025 from which between 2200 and 825 tonnes could potentially enter the ocean as marine debris. The proposed action would largely contribute to reduce this amount and so to the target 14.1 "By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution" measured through the official indicator 14.1.1.b – Floating plastic debris density (measured in particles/km^2).

Indirectly, other SDGs can be benefited from this measure such as SDG 12 – for the SBSey scenarios in which compost is produced in Seychelles, the quantity of organic waste going to landfilling will be reduced since it will be diverted to the composting plant and measured through the official indicator 12.3.1.b – Food waste index.

5. Limitations of the study

Due to the scope of this paper, the techno-economic assessment is performed as a preliminary ballpark estimation that entails high uncertainty on the final cost assumptions (around 20%). Further uncertainty concerns also waste composition and SDSW data which are obtained from recent studies. This limitation affecting consequently to the evaluation of analysis and results. In order to perform a more detailed cost estimation, further data collected on-site would be needed.

Another limitation of this study is the exclusion the risk factor that might reduce the potential emission reduction for each scenario, and consequently the quantity of CER issued (UNEP, 2007b). Further research should include the quantification of the most influencing risks that are briefly explained herein:

Performance risk – usually the project performance is overestimated and the quantity of issued CERs can be lower than expected for several reasons such as time lag due to construction and commissioning activities, technology transfer problems, overestimation of outputs projected due to model inaccuracies, and unpredictable operating conditions.

Monitoring risk – once the project is registered, it will only produce CERs if monitoring is carried out adequately and correctly according to the procedure previously set out in the monitoring plan. As stated by Huber-Humer et al. (2009) the reliable quantification of mitigated emissions through biocovers is very complex and one of the main challenges is to set the parameters, methods and procedures to quantify them. An improper procedure or data not sufficiently accurate will reduce the quantity of CERs issued.

6. Conclusions

Full coastal landfills without a proper closure and maintenance are common in SIDS mainly due to the high touristic pressure and the lack of economic resources and knowledge to address waste issues. Those landfills are large sources of GHGs (main cause of the climate change) and marine debris, among other environmental impacts. The closure of landfills and the avoidance of GHGs is an urgent topic and a major challenge for SWM systems. CDM appears as a possibility to facilitate sustainable financing and thus this paper presents a techno-economic and environmental assessment of a MOL implementation in the Providence Landfill (Seychelles) as a small-scale CDM measure.

The main conclusions drawn from results are:

1. The profitability of this kind of measure is clearly dependent on the existence of SB material within the SIDS. Importing material from the continent, usually at high prices due to transport and taxes, render the CDM measure unprofitable. For that reason, before implementing the CDM activity, it is important to verify the yearly availability of SB and try to foster composting technology within the waste management system. Further research on this line should evaluate the possibility of bundling both actions, the compost production and the MOL application under the CDM framework.

2. According to the results, the MOL measure starts to be profitable in some scenarios for CER prices higher than 26 €/t CO_2 eq. that might seem unrealistic comparing to the actual price of CERs in the market (i.e. 0.3 €/t CO_2 eq.), but that seem possible in the future depending on the CORSIA development. Concerning the number of years to complete the MOL application, benefits increase with a decreasing number of years. It is important to consider that those options have to be evaluated by the decision-makers considering the availability of SB in the market (both locally and internationally) and the estimated labour force and local capacity to implement the MOL. Concerning the crediting period, as expected, benefits increase with the increasing number of years in which the CDM allows receiving CERs. Further research in this line should include the risk component, crucial for decision-makers, that increases for increasing CPs.
3. Finally, results also show that even if the MOL measure is not profitable under the CDM, it might be a cost-effective option for CO_2 emission abatement from the domestic climate effort under the Paris agreement, as well as it contributes to certain SDG achievement – mainly SDG8, SDG13, and SDG14.

When implementing MOL measures it is known that higher GHG emission reductions and profitability are achieved for landfills covered right after they reach the full capacity, highlighting the importance of implementing the MOL measure the sooner the better, and calling for a prompt action in Seychelles.

It is important to highlight that the techno-economic and environmental assessment presented in this paper can be considered a first step towards the complete feasibility and sustainability assessment of the project idea. The final decision of implementing a biocover in the Providence landfill in Seychelles should be taken after considering different waste management scenarios that integrate environmental, social and economic criteria, as well as a life cycle thinking approach, in order to achieve sound sustainable waste management practices.

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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