Optimization of a Landfill Gas Collection
Shutdown Based on an Adapted First-Order
 Decay Model

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ABSTRACT

LandGEM’s equation was reformulated to include two types of refuse, fast decaying refuse (FDR) and slow decaying refuse (SDR), whose fractions and key modeling parameters $k$ and $L_0$ were optimized independently for three periods in the life of the Montreal-CESM landfill. Three scenarios were analyzed and compared to actual biogas collection data: 1) Two-Variable Scenario, where $k$ and $L_0$ were optimized for a single type of refuse; 2) Six-Variable Scenario, where three sets of $k$ and $L_0$ were optimized for the three periods and for a single type of refuse; and 3) Seven-Variable Scenario, whereby optimization was performed for two sets of $k$ and $L_0$, one associated with FDR and the second with SDR, and for the fraction of FDR during each of the three periods. Results showed that the lowest error from the error minimization technique was obtained with the Six-Variable Scenario. However, this scenario’s estimation of gas generation was found to be rather unlikely. The Seven-Variable Scenario, which allowed for considerations about changes in landfilling trends, offered a more reliable prediction tool for landfill gas generation and optimal shutdown time of the biogas collection system, when the minimum technological threshold would be attained. The methodology could potentially be applied mutatis mutandis to other landfills, by considering their specific waste disposal and gas collection histories.

KEYWORDS: Landfill gas collection; First-order decay model; LandGEM; IPCC model; Fast-decaying refuse; Slow-decaying refuse
INTRODUCTION

When landfill methane (CH\textsubscript{4}) generation reaches a critical low value, the system employed to burn biogas must be replaced or, conditions permitting, shut down. The decision-making process is challenging because of the difficulty in predicting relatively accurate future trends sufficiently in advance. This is the type of challenge being faced by the operator of the Montreal CESM landfill. This 72-ha site, which accepted refuse from 1968 to 2008, is located in a former limestone quarry, in a (now) densely populated area of Montreal. The depth of refuse reaches 80 m in certain areas, and it is estimated that some 40 million tons of refuse from various origins were landfilled at the CESM landfill site. Prior to the beginning of the landfill operations, the bottom and side walls of the former quarry were not impermeabilized. As a consequence, most of the waste mass is virtually saturated. The database for this site included 41 years of landfilling data and a compilation of daily entries of 20 years of biogas collection data.

Current methods to predict landfill gas generation include first-order decay U.S. EPA’s Landfill Gas Emissions Model (LandGEM) (USEPA, 2005), which considers only one type of municipal solid waste (MSW) for the entire lifetime of a site. The two key parameters in LandGEM are \(L_0\), which represents the methane production potential (m\textsuperscript{3} Mg\textsuperscript{-1} wet waste) and \(k\), which represents the first-order decay rate associated with waste decomposition (yr\textsuperscript{-1}) (USEPA, 2005). Some models, such as the one proposed by the Intergovernmental Panel on Climate Change (IPCC, 2006), allow for a multiphase refuse input, which could potentially lead to more precise predictions. However, a common predicament in landfill management is the lack of information regarding landfilling history.
and/or lack of specific data about refuse categories and subcategories. This is particularly true for old sites, such as the CESM landfill, which had no guidelines or regulations regarding keeping track of the nature of admitted refuse. This study proposes a methodology of reformulation of a first-order model. It aims at improving model predictive performance using available information about the history of the site and gas collection data.

In the past 2 decades, societal changes in landfilling practices have occurred as a result of stricter legislation, improvements in recycling, higher raw material value, etc. One important example of legislation-driven change is the imposed reduction in landfilling of organic matter in the European Union (Directive 1999/31/EC). Quebec’s (Canada) recent governmental policy (“Quebec Residual Materials Management Policy”) is now calling for the banishment of organic matter in landfills in this province by the year 2020. Changes in waste characteristics need to be taken into account in biogas generation modeling; for example, by using values of $k$ and $L_0$ that evolve throughout the site’s history. The first important characteristic of the proposed methodology was therefore the subdivision of the lifetime of the CESM landfill into 3 distinct periods – 1968-1989 / 1990-1999 / 2000-2008 – that reflect the specific history of refuse admittance, i.e. changes in the characteristics of the wastes. As mentioned previously, while data about quantities landfilled could be found for the entire lifetime of the site, specific data about refuse categories were not available.

It is proposed to distinguish herein two distinct categories of landfill refuse, namely fast decaying refuse ($FDR$) and slow decaying refuse ($SDR$). For instance, as per IPCC-recommended $k$ values, food waste in MSW having a high value of $k$ was segregated as $FDR$, whereas materials whose $k$ values are low, such as wood-straw waste, were assigned
to the SDR category. The specific segregation of refuse in either FDR or SDR is presented in Table 1. Based on the $k$ value, once a type of waste was categorized as either FDR or SDR, its minimum and maximum $L_0$ values (given as mass of degradable organic carbon; DOC) were assigned following IPCC (2006) recommendations for this type of waste. Given the lack of precise information about the characteristics of the waste, it was decided to limit segregation of the bulk waste to these two main categories.

According to IPCC-recommended $L_0$ and $k$ values (IPCC, 2006), FDR can be characterized by low values of $L_0$ and fast kinetics (high values of $k$), while SDR is characterized by high methane generation potentials (high values of $L_0$) and slow kinetics (low values of $k$). These considerations about $k$ and $L_0$ values are generalizations of the observed tendencies in IPCC-recommended $k$ and $L_0$ values and are representative of the bulk behaviour of the waste mass and not that of specific components. This approximation results in the overlapping of FDR and SDR $L_0$ values, as discussed when presenting the data in Table 2. It is considered herein that a decrease in the quantity of landfilled FDR results in a decrease of the bulk mass’ $k$ value and an increase in $L_0$. An important caveat is given by Wang et al. (2011) (Wang et al., 2011), who have shown that component-specific low decay rates among species of wood do not necessarily correlate with high methane yields. In this study, the magnitude of the variation in $L_0$ is a resultant of the optimization technique, which sets $L_0$ within IPCC-recommended ranges.

Table 1 - Segregation of FDR and SDR and corresponding $k$ values as per IPCC recommended ranges. Adapted from IPCC (2006).
These adaptations of the biogas generation modeling process were considered in order to
develop a more reliable management tool to predict landfill gas generation. So far,
LandGEM has been used at the CESM landfill.

By attributing independent values of $k$ and $L_0$ and different fractions between $FDR$ and
$SDR$ that best reflected the changing proportions of admitted refuse during the 3 periods
mentioned previously, the same first-order model equation used in LandGEM was adapted
to generate production curves. Minimization of error between modeled generation and
generated gas helped to find the best fitting curve, i.e. the optimized values of $k$, $L_0$, and
fraction of $FDR$ for each period. In an intermediate step, collection data were transformed
into generation data by adopting a fixed recovery efficiency rate.

The objective is to use the optimized generation curves to predict the optimal moment to
shut down the biogas collection system, when the minimum technological threshold (MTT)
would be attained. The optimized values of the independent variables were tested against
the known history of refuse admittance. In principle, the methodology adopted could be
replicated to other landfills, by considering the specific evolution of the $FDR$ fraction in
the landfilled waste and the available gas collection database.

 METHODS

 Landfill gas collection and landfilled mass data
Landfill gas (LFG) collection data were obtained between 1994 and 2013. For this period, yearly compilations were performed using daily biogas collection data. A global relative error of 2.9% was calculated for the flowmeter and chromatograph used to measure collected CH$_4$ at the CESM landfill (Lagos, 2014). The total landfilled mass was determined on a yearly basis starting in the opening year, in 1968, until its closure, in 2008. The types of refuse admitted were mainly household, commercial, institutional and industrial waste, as well as construction and demolition debris. The latter included inert (non LFG-generating) matter such as, asphalt, concrete and bricks.

**Transformation from gas collection to generation data**

Gas collection data were transformed into generation data by setting a recovery efficiency percentage that remained constant throughout the lifetime of the site. The main analysis (presented in detail herein) was performed with an efficiency rate considered as excellent in the literature, i.e. 75% (Spokas et al., 2006; Spokas et al., 2015). Given the proximity of this landfill to housing developments, the presence of an extensive active gas collection system (consisting of over 260 LFG collection wells), and a history of very low measured emissions, high efficiencies can be considered plausible for this specific site (Franzidis et al., 2008; Héroux et al., 2010). According to IPCC (2006), higher than 75% collection efficiencies can only be attributed to properly capped sites with well-designed and well-operated gas recovery systems. In order to evaluate how the year of occurrence of MTT is affected by gas collection efficiency, MTT was obtained for the following recovery efficiency values: 55%, 65%, 75%, 85%, and 95%.
Scenarios considered

Based on refuse admittance history at CESM – including the ban of landfill organic matter in 2000 – and societal changes triggered by new recycling policies, the lifetime of this site was subdivided into 3 distinct periods: 1968–1989, 1990–1999 and 2000–2008. The extension of period 3 beyond the end of landfilling (2008) is justified by the need to predict methane generation to estimate the year of occurrence of MTT and the onset of aftercare.

The beginning of period 3 was easily determined; it coincided with the ban on organic matter (FDR) admittance at CESM, in May 2000. The beginning of period 2 was chosen based on the implementation of recycling programs in the Province of Quebec in the early 1990s. Given the fact that it is difficult to identify exactly when recycling programs became effective – therefore affecting the fractions of landfilled FDR and SDR –, the sensitivity of the transition between periods 1 and 2 was tested by setting it 4 years before and 4 years after 1990. This test was performed only for the Seven-Variable Scenario (presented hereafter).

Refuse admitted in each of the three periods had particular characteristics that distinguished it. Therefore, the fractions of landfilled FDR and SDR eventually became one of the variables of this parametric study, which was performed based on the following three scenarios, illustrated in Figure 1: 1) Two-Variable Scenario, for which one single set of the parameters $k$ and $L_0$ characterized the refuse for the entire lifetime of the site. This scenario corresponds to the current simple phase formulation of LandGEM; 2) Six-Variable Scenario, for which one set of $k$ and $L_0$ values would be selected for the refuse in each of the three key periods; and 3) Seven-Variable Scenario, for which two sets of $k$ and $L_0$ values were adopted: one characterizing FDR and the other SDR. Both sets remained the same.
throughout the entire study period. However, 3 fractions of FDR in the refuse were adopted, one for each of the 3 key periods. All variables in these 3 scenarios were optimized within predetermined ranges as per IPCC (2006) recommendations.

It is obvious that a simple increase in the number of independent variables would lead to an improvement in model fit. But this would be meaningless if the optimization process did not include considerations about what really happened during the history of this landfill, in particular concerning the characteristics of the wastes landfilled. For example, an optimization result indicating that the site saw an increase in FDR over time would not be coherent with the fact that there was a ban in landfilling of organic matter at the beginning of period 3. Such an optimization result would therefore have to be rejected. In short, the 2, 6 or 7 variables in each model are not truly independent as each model must be both internally consistent (i.e. the relative value of each variable must be plausible) and correspond to reality.

Figure 1 - Schematic of the three scenarios and their corresponding variables.

Modeling variables and their optimization ranges

As shown in Figure 1, variables were labeled in the following manner: 1) $k$ and $L_0$, for the Two-Variable Scenario; 2) $k_1$, $k_2$, $k_3$, $L_{01}$, $L_{02}$ and $L_{03}$, for the Six-Variable Scenario; and 3) $L_0$-FDR, $L_0$-SDR, $k$-FDR, $k$-SDR, $f_1$-FDR, $f_2$-FDR and $f_3$-FDR, for the Seven-Variable
Scenario. The subscript $n = 1, 2$ or 3 denotes the landfilling period to which the variable belongs, while $f_1$, $f_2$ and $f_3$ denote the fractions of FDR in the refuse.

The ranges within which $k$, $L_0$, $k_n$, $L_{0n}$ and $f_n$FDR could vary during optimization were chosen to allow maximum flexibility while keeping values within IPCC recommended ranges and realistic in relation to the documented landfilling history. Optimization ranges for $k$ and $L_0$ were based on IPCC recommended values for FDR (i.e. food and municipal sludge) and SDR (i.e. cellulose and textiles) (IPCC, 2006). Values for $k$ were taken from the Very Humid Tropical Climate category. This is assumed to be valid, since the CESM landfill is situated in an old quarry, with considerable influx of groundwater (Héroux, 2008). $L_0$ values, expressed as DOC, were converted into $L_0$ using equation 1, as follows:

$$L_0 = F \, DOC \, DOC_f \left(\frac{16}{12}\right) \, MCF$$

where $F$ is the fraction of CH$_4$ in generated landfill gas; $DOC_f$ is the fraction of dissimilated organic carbon; $16/12$ is the molecular weight ratio of CH$_4$ to C and $MCF$ is the correction factor for aerobic decomposition (IPCC, 2006; Thompson et al., 2009).

The value of $F$ was averaged at 0.56 from daily measurements of CH$_4$ and CO$_2$ in the collected landfill gas at CESM between 2001 and 2013. $DOC_f$ was set at 0.5 (default value according to IPCC) and $MCF$ at 1.0, as recommended by IPCC (2006) for a site under anaerobic conditions, such as the CESM landfill. Mass units of DOC were then converted to volumetric units using a CH$_4$ volumetric mass of 714 g m$^{-3}$. While recent work by Wang et al. (2011) shows that $DOC_f$ can significantly vary with the nature of waste, the default
IPCC value of 0.5 is considered constant in this study. This fact may be of interest in future studies in order to reduce uncertainties in the transformation of DOC to \( L_0 \).

Table 2 presents \( k \) and \( L_0 \) optimization ranges for the three scenarios. The choice – among IPCC recommendations – of what is considered a very high \( k \) value for a North American landfill is partly justified by the high degree of saturation of the refuse. Furthermore, work by De la Cruz and Barlaz (2010) shows that component-specific IPCC-recommended \( k \) values for food waste and garden-park waste were underestimated by 200% and 400% respectively. Wang et al. (2013) also concluded that higher values than usually recommended in the literature can be adopted in certain cases.

The ranges of values for each of the two categories of waste of the Seven-Variable Scenario \((FDR \text{ and } SDR)\) were also taken from IPCC (2006). The optimization range of \( L_0 \) corresponds to the minimum and maximum \( L_0 \) found for the same waste categories considered in \( FDR \) and \( SDR \) segregation. The maximum and minimum values of \( k \) and \( L_0 \) for each category of waste were selected to create a single optimization range. It can be observed that there is some degree of overlapping of \( FDR \) and \( SDR \) \( L_0 \) values between 105 and 115 m\(^3\) CH\(_4\) Mg\(^{-1}\). In other words, the subdivision into \( FDR \) and \( SDR \) is not clear-cut.

As mentioned previously, this overlap can be attributed to the generalizations of the trends observed in IPCC-recommended \( k \) and \( L_0 \) values, which are representative of the bulk behaviour of the waste mass and not that of specific components.
The FDR fractions of the Seven-Variable Scenario were estimated for each of the three periods. For period 2, \( FDR = 56\% \) and \( SDR = 44\% \). These estimates were based on a study that characterized refuse landfilled in 2000, in the Province of Quebec (RECYC-QUÉBEC, 2000). For period 3, based on a characterization study performed at the CESM site in 2006 (Baillargeon et al., 2006), fractions for \( FDR \) and \( SDR \) were set at 5% and 95% respectively. Since the contribution of inert matter – such as concrete, asphalt and bricks – in generating LFG is, for all practical purposes, negligible, it was taken out of the mass balance when calculating \( FDR \) and \( SDR \) fraction estimates. For period 1, no characterization study could be found relating to \( FDR \) or \( SDR \) fractions. Nonetheless, it was expected that before period 2, when recycling had yet to become common practice, a smaller fraction of \( FDR \) was landfilled (indeed, greater quantities of paper and cardboard ended up in the landfill). Based on available information, an estimated fraction of 25% was therefore adopted for \( FDR \) in period 1. Figure 2 shows the variation of these values throughout the lifespan of the site.

**Erreur ! Source du renvoi introuvable.** presents the optimization ranges for \( FDR \) fractions in the Seven-Variable Scenario. The adopted optimization range for the \( FDR \) fraction is wide, since it reflects the uncertainty resulting from lack of information for this site, and the estimative nature of characterization studies. Nonetheless, it is worthwhile repeating that the results must be anchored in reality. They must reflect the actual history of landfiling; otherwise, this study would be a mere fitting exercise.
Figure 2 - Schematic representation of the evolution of estimated $FDR$ and $SDR$ fractions at CESM from opening (1968) to closure (2008).

Table 3 - Optimization ranges for FDR fractions in the Seven-Variable Scenario for the three periods considered.

**LandGEM formulation**

LandGEM is based on the following first-order decomposition rate equation:

$$Q_{CH_4 n} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k \cdot L_0 \left( \frac{M_i}{10} \right) e^{-kt_{ij}}$$  \hspace{1cm} (2)

where $Q_{CH_4 n} =$ annual methane generation in the $n^{th}$ year of the calculation (m$^3$ yr$^{-1}$); $k =$ methane generation rate (yr$^{-1}$); $L_0 =$ potential methane generation capacity (m$^3$ Mg$^{-1}$); $M_i =$ mass of waste accepted in the $i^{th}$ year (Mg); $t_{ij} =$ age of the $j^{th}$ section of waste mass $M_i$ accepted in the $i^{th}$ year (decimal years); $i = 1$ year time increment; $j = 0.1$ year time increment; and $n =$ number of years in the calculation, i.e. year of calculation – initial year of waste acceptance (USEPA, 2005).

For the Six- and Seven-Variable Scenarios, LandGEM calculations were rewritten in an Excel spreadsheet to be able to assign different sets of variables to each of the three periods.

**Error minimization technique**
The sum of squared errors (SSE) between gas collection data and modeled results was minimized by means of the Generalized Reduced Gradient nonlinear method using a commercial spreadsheet. The SSE is described by equation 3, as follows:

\[
SSE = \sum_{i=1}^{n} (Q_{mi} - Q_{ci})^2
\]  

(3)

where \(n\) = number of yearly values of available collection data; \(i\) = year of calculation; \(Q_{mi}\) = measured generated methane in the \(i^{th}\) year (\(m^3\) yr\(^{-1}\)); and \(Q_{ci}\) = generated methane in the \(i^{th}\) year calculated by equation 2 (\(m^3\) yr\(^{-1}\)).

The unicity of the optimized results presented herein was evaluated by scanning the model variables within predetermined limits and computing SSE values for each set of selected parameters. This is illustrated in Figure 3, which presents the SSE values for \(10^4\) combinations of \(k\) and \(L_0\) values (100×100) of the Two-Variable Scenario, for recovery efficiencies equal to 55%, 75% and 95%. The minimal SSE is found in the region represented by the darkest zone, which was set by an error range within 10% of the SSE. This zone confirms the presence of a single localized minimum. Similar behaviour was obtained for the Six- and Seven-Variable Scenarios.

Figure 3 – Model-predicted errors for the Two-Variable Scenario as function of recovery efficiency.
RESULTS AND DISCUSSIONS

Figure 4 shows CH$_4$ generation obtained by the reformulated LandGEM equation, for the three scenarios considered. The curve with solid points represents data collected from 1994 to 2013 that were transformed into generation values by considering 75% recovery efficiency. The lowest SSE value was obtained for the Six-Variable Scenario. Accordingly, the best fit with generation data (based on actual collection) was obtained for this scenario. It was followed by the Seven-Variable and Two-Variable Scenarios with respective SSE values 2.6 and 6.3 times higher.

Scenarios were analyzed in terms of their ability to predict when the MTT would be attained. In the case of the CESM landfill facility, MTT is approximately 10 Mm$^3$ yr$^{-1}$. Below this value, LFG collection would no longer be sustainable with the present gas collection system.

Figure 4 - Modeled CH$_4$ generation for the Two-, Six- and Seven-Variable Scenarios as optimized after SSE minimization relative to measured CH$_4$ generation.

Two-Variable Scenario

This scenario considers a single type of refuse admitted throughout the landfill’s operating life. According to this scenario, the MTT would be reached in 2017. Based on latest available data (2012 and 2013), CH$_4$ generation seems to be underestimated.
Values of $k$ and $L_0$ optimized by SSE minimization were $0.197 \text{ yr}^{-1}$ and $127 \text{ m}^3 \text{ CH}_4 \text{ Mg}^{-1}$ respectively. The relatively high $k$ and low $L_0$ would indicate a refuse with a high proportion of $FDR$, which is not necessarily the case for the refuse landfilled at the CESM site. This is an indication that this model does not coincide with actual landfill history and therefore needs refining.

### Six-Variable Scenario

This scenario also considers a single type of refuse but landfiling was subdivided into the three periods indicated in Erreur ! Source du renvoi introuvable.; each with its own independently optimized values of $k$ and $L_0$. Since the optimization ranges for $k$ and $L_0$ were the same for all three periods, these variables were free to increase or decrease from one period to the next.

Optimized values for $k_1$, $k_2$, $k_3$, $L_{01}$, $L_{02}$ and $L_{03}$ were $0.282 \text{ yr}^{-1}$, $0.081 \text{ yr}^{-1}$, $0.030 \text{ yr}^{-1}$, $194 \text{ m}^3 \text{ CH}_4 \text{ Mg}^{-1}$, 241 $\text{ m}^3 \text{ CH}_4 \text{ Mg}^{-1}$ and 21 $\text{ m}^3 \text{ CH}_4 \text{ Mg}^{-1}$ respectively. The decrease in optimized $k$ values – and increase in $L_0$ values – between periods 1 and 2 implies that the fraction of $FDR$ within the waste would also have decreased. Yet this is not corroborated by historical data. Indeed, recycling programs deployed in the early 1990s led to an important decrease in landfilling of paper and cardboard ($SDR$ fraction), which caused an increase in the fraction of $FDR$ in subsequent years (Figure 2).

Values of optimized $L_0$ decreased between periods 2 and 3, implying that the fraction of $SDR$ would also have decreased. Again, this trend is not backed up by the CESM landfiling history. In 2000, CESM forbade admission of $FDR$, such as household waste, hence increasing $SDR$ fractions. These mismatches between optimization of the variables and
known refuse admittance history suggest that the Six-Variable Scenario could not be
retained, despite the fact that the lowest SSE value was obtained with it. Furthermore,
before 1992 the modeled curve seems to greatly overestimate CH\textsubscript{4} generation in
comparison with the other two scenarios with a \~\,100 Mm\textsuperscript{3} difference at generation peak
in 1990. Such an additional volume of landfill gas seems unlikely given the environmental
nuisances that would have resulted for workers and the surrounding population; a nuisance
that was never observed. Accordingly, the Six-Variable Scenario was deemed
inappropriate to explain the behaviour of LFG generation for this site. According to the
Six-Variable Scenario, the MTT would be reached in 2028.

**Seven-Variable Scenario**

This scenario considers two types of refuse and their fractions that vary along the three
periods indicated in **Erreur ! Source du renvoi introuvable.**. Since the optimization
ranges for the \textit{FDR} fractions shown in **Erreur ! Source du renvoi introuvable.** are
different but overlap between periods 1 and 2, optimized \(f_{\text{1}}\)-\textit{FDR} could increase or decrease
along these periods. The optimization ranges for the \textit{FDR} were different and decreased
from period 2 to period 3. Accordingly, optimized \(f_{\text{1}}\)-\textit{FDR} was expected to decrease from
period 2 to period 3.

Optimized values for \(k\)-\textit{FDR}, \(k\)-\textit{SDR}, \(L_{\text{0}}\)-\textit{FDR}, \(L_{\text{0}}\)-\textit{SDR} were, 0.363 yr\textsuperscript{-1}, 0.085 yr\textsuperscript{-1}, 115 m\textsuperscript{3}
\text{CH\textsubscript{4}} Mg\textsuperscript{-1}, 105 m\textsuperscript{3} CH\textsubscript{4} Mg\textsuperscript{-1}, respectively. Moreover, the optimized values for \(f_{\text{1}}\)-\textit{FDR}, \(f_{\text{2}}\)-\textit{FDR} and \(f_{\text{3}}\)-\textit{FDR} were 11%, 70% and 5%, respectively. Contrary to the Six-Variable
Scenario, there is no mismatch between optimized \textit{FDR} and \textit{SDR} fractions and the history
of refuse admittance. The value of optimized \(k\)-\textit{SDR} is nearly four times lower than that of

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\( k\text{-FDR} \) and the value of optimized \( L_0\text{-SDR} \) is moderately higher than that of \( L_0\text{-FDR} \).

According to the Seven-Variable Scenario, the MTT would be reached by 2027.

The Seven-Variable Scenario allows for consideration of changes in landfilling trends, as reflected in variations of \( FDR \) and \( SDR \) fractions. This is a clear added-value to the simple phase Two-Variable Scenario. In addition, contrary to the Six-Variable Scenario, the optimized variables of the Seven-Variable Scenario better reflect the landfilling history. For these reasons, the year 2027 – when the Seven-Variable Scenario is expected to reach the MTT – is a more reliable prediction for gas collection shutdown. Figure 5 shows MTT for the Two- and Seven-Variable Scenarios.

Figure 5 – Minimum Technological Threshold for the Two- and the Seven-Variable Scenarios.

**Effect of the variation of landfill gas recovery efficiency**

The results presented above were obtained by adopting 75% recovery efficiency throughout the lifetime of the CESM landfill. The effect of recovery efficiency on the MTT year of occurrence and on the SSE for the three scenarios was tested by varying it from 55% to 95% in increments of 10 percentage points. At each increment, a new optimization was performed for each scenario. The results obtained are presented in Figure 6, which shows that when the recovery efficiency is increased from 75% to 95%, the MTT occurs
1, 3 and 2 years earlier, for the Two-, Six- and Seven-Variable Scenarios, respectively. For all practical purposes, these differences can be considered relatively small. The results of Figure 6 also show that, regardless of the value of the recovery efficiency, the Six-Variable Scenario consistently had the lowest SSE. The decrease in SSE becomes smaller as recovery efficiency increases and seems to level off when the recovery efficiency reaches 75%.

Although not apparent in the results presented in Figure 6, our analyses show that for all tested efficiencies, the Seven-Variable Scenario seemed to better reflect the landfilling history at the Montreal-CESM landfill, while the Six-Variable Scenario presented the same discrepancy between optimized values and landfilling history, as previously mentioned.

High LFG recovery efficiencies are expected in this landfill due to the more than 250 biogas collection wells installed. Numerous surface and lateral migration surveys have shown that surface fluxes have been very low. It is up to the operator to consider the efficiency level he/she feels comfortable with when estimating the year of occurrence of MTT for this particular site.

Effect of start of transition year between periods 1 and 2
The sensitivity of the choice made for the transition year between periods 1 and 2 – when recycling programs became effective, therefore affecting landfilled \textit{FDR} and \textit{SDR} fractions – was assessed for the Seven-Variable Scenario and for 95\% recovery efficiency. Figure 7 shows the effect of moving the end-of-period four years back or forward, relative to 1990. As the limit year was moved from 1986 to 1994, there was a minimal effect on modeled generation values after the generation peak.

Figure 7 - Effect of the variation of the limit year between periods 1 and 2 on the modeling of \textit{CH}_4 generation for the Seven-Variable Scenario.

\textbf{FURTHER DISCUSSIONS AND LIMITATIONS}

The method proposed in this study accounts for the variation in the nature of admitted refuse at landfill sites, which is a consequence of changes in the environmental consciousness of societies – in turn reflected in stricter regulations – and the economics of waste management. Consideration of how these socio-economic changes affect landfill gas generation is crucial when it comes to making decisions about the fate of systems put in place to reduce the environmental impact of landfills and increase their economic viability.

Errors associated with measurements of various gas concentrations at the CESM landfill can be considered minor, due, in part, to continuous gas quality monitoring and the quality control assured by the well-equipped laboratory on site. However, high operational variances may have caused the bumps in the generation curve observable in the years 2000
and 2012 (Figure 4). These variances can be attributed to a myriad of causes, including: re-
excavation and re-landfilling of waste, temporary difficulties with the gas or leachate
collection systems (such as defective wells), localized settlements, localized elevated
temperatures, etc. Consideration of variable recovery efficiency could account, at least in
part, for the operational variances; hence the interest in considering it in further works. As
shown in this study, these limitations did not seem to influence the fact that the Seven-
Variable Scenario was found to be the most appropriate scenario to estimate shutdown
time, despite the fact that its minimization error was not the lowest.

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List of Tables

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<th>Type of Waste</th>
<th>Climate Zone*</th>
<th>Boréal et Tempéré (MAT ≤ 20°C)</th>
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<tr>
<td>Slowly degrading waste</td>
<td>Paper/textiles waste</td>
<td>0.04</td>
<td>0.03&lt;sup&gt;3,4&lt;/sup&gt; – 0.05&lt;sup&gt;3,4&lt;/sup&gt;</td>
</tr>
<tr>
<td>SDR</td>
<td>Wood/straw waste</td>
<td>0.02</td>
<td>0.01&lt;sup&gt;3,4&lt;/sup&gt; – 0.03&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Moderately degrading waste</td>
<td>Other (non-food) organic putrescible/Garden and park waste</td>
<td>0.05</td>
<td>0.04 – 0.06</td>
</tr>
<tr>
<td>FDR</td>
<td>Rapidly degrading waste</td>
<td>Food waste/Sewage sludge</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 1 - Segregation of FDR and SDR and corresponding k values as per IPCC recommended ranges. Adapted from IPCC (2006).

<table>
<thead>
<tr>
<th>Optimization range for k (yr&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Optimization range for L&lt;sub&gt;0&lt;/sub&gt; (m&lt;sup&gt;3&lt;/sup&gt; CH&lt;sub&gt;4&lt;/sub&gt; Mg&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Variable Scenario  [0.030–0.700]</td>
<td>[21–241]</td>
</tr>
<tr>
<td>Six-Variable Scenario                  [0.030–0.700]</td>
<td>[21–241]</td>
</tr>
<tr>
<td>Seven-Variable Scenario</td>
<td>FDR [0.100–0.700]</td>
</tr>
<tr>
<td></td>
<td>SDR [0.030–0.085]</td>
</tr>
</tbody>
</table>

Table 2 - k and L<sub>0</sub> optimization ranges for the Two-, Six- and Seven-Variable Scenarios (Based on IPCC (2006) values).
Table 3 - Optimization ranges for FDR fractions in the Seven-Variable Scenario for the three periods considered.

<table>
<thead>
<tr>
<th>Period</th>
<th>Optimization range for landfilled FDR fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2: 1990–1999</td>
<td>[30–70]</td>
</tr>
<tr>
<td>3: 2000–2008</td>
<td>[0–10]</td>
</tr>
</tbody>
</table>
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