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_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^3 Mg^{-1} wet waste) and k, which represents the first-order decay rate associated with waste decomposition (yr^{-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 mesure 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

186 Scenario. The subscript $n = 1, 2$ or 3 denotes the landfilling period to which the variable
187 belongs, while f_1, f_2 and f_3 denote the fractions of *FDR* in the refuse.

188 The ranges within which k, L_0, k_n, L_{0n} and f_n-*FDR* could vary during optimization were
189 chosen to allow maximum flexibility while keeping values within IPCC recommended
190 ranges and realistic in relation to the documented landfilling history. Optimization ranges
191 for k and L_0 were based on IPCC recommended values for *FDR* (i.e. food and municipal
192 sludge) and *SDR* (i.e. cellulose and textiles) (IPCC, 2006). Values for k were taken from
193 the Very Humid Tropical Climate category. This is assumed to be valid, since the CESM
194 landfill is situated in an old quarry, with considerable influx of groundwater (Héroux,
195 2008). L_0 values, expressed as *DOC*, were converted into L_0 using equation 1, as follows:

196 $$L_0 = F\ DOC\ DOC_f \left(\frac{16}{12}\right) MCF \qquad (1)$$

197 where F is the fraction of CH_4 in generated landfill gas; DOC_f is the fraction of dissimilated
198 organic carbon; $16/12$ is the molecular weight ratio of CH_4 to C and *MCF* is the correction
199 factor for aerobic decomposition (IPCC, 2006; Thompson et al., 2009).

200 The value of F was averaged at 0.56 from daily measurements of CH_4 and CO_2 in the
201 collected landfill gas at CESM between 2001 and 2013. DOC_f was set at 0.5 (default value
202 according to IPCC) and *MCF* at 1.0, as recommended by IPCC (2006) for a site under
203 anaerobic conditions, such as the CESM landfill. Mass units of *DOC* were then converted
204 to volumetric units using a CH_4 volumetric mass of 714 g m^{-3}. While recent work by Wang
205 et al. (2011) shows that DOC_f can significantly vary with the nature of waste, the default

206 IPCC value of 0.5 is considered constant in this study. This fact may be of interest in future
207 studies in order to reduce uncertainties in the transformation of *DOC* to L_0.

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

215 The ranges of values for each of the two categories of waste of the Seven-Variable Scenario
216 (*FDR* and *SDR*) were also taken from IPCC (2006). The optimization range of L_0
217 corresponds to the minimum and maximum L_0 found for the same waste categories
218 considered in *FDR* and *SDR* segregation. The maximum and minimum values of k and L_0
219 for each category of waste were selected to create a single optimization range. It can be
220 observed that there is some degree of overlapping of *FDR* and *SDR* L_0 values between 105
221 and 115 m^3 CH_4 Mg^{-1}. In other words, the subdivision into *FDR* and *SDR* is not clear-cut.
222 As mentioned previously, this overlap can be attributed to the generalizations of the trends
223 observed in IPCC-recommended k and L_0 values, which are representative of the bulk
224 behaviour of the waste mass and not that of specific components.

225

226 Table 2 - k and L_0 optimization ranges for the Two-, Six- and Seven-Variable Scenarios
227 (Based on IPCC (2006) values).

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 landfilling; 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:

$$Q_{CH_4 n} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k\, L_0 \left(\frac{M_i}{10}\right) e^{-k t_{i,j}} \qquad (2)$$

where Q_{CH4n} = 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:

$$SSE = \sum_{i=1}^{n} (Q_{mi} - Q_{ci})^2 \quad (3)$$

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 yr^{-1} and 127 m^3 CH_4 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 landfilling 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 yr^{-1}, 0.081 yr^{-1}, 0.030 yr^{-1}, 194 m^3 CH_4 Mg^{-1}, 241 m^3 CH_4 Mg^{-1} and 21 m^3 CH_4 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 landfilling 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_4 generation in comparison with the other two scenarios with a ~ 100 Mm^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 *FDR* fractions shown in **Erreur ! Source du renvoi introuvable.** are different but overlap between periods 1 and 2, optimized f_n-*FDR* could increase or decrease along these periods. The optimization ranges for the *FDR* were different and decreased from period 2 to period 3. Accordingly, optimized f_n-*FDR* was expected to decrease from period 2 to period 3.

Optimized values for *k-FDR*, *k-SDR*, L_0-*FDR*, L_0-*SDR* were, 0.363 yr^{-1}, 0.085 yr^{-1}, 115 m^3 CH_4 Mg^{-1}, 105 m^3 CH_4 Mg^{-1}, respectively. Moreover, the optimized values for f_1-*FDR*, f_2-*FDR* and f_3-*FDR* were 11%, 70% and 5%, respectively. Contrary to the Six-Variable Scenario, there is no mismatch between optimized *FDR* and *SDR* fractions and the history of refuse admittance. The value of optimized *k-SDR* is nearly four times lower than that of

351 *k-FDR* and the value of optimized L_0-*SDR* is moderately higher than that of L_0-*FDR*.
352 According to the Seven-Variable Scenario, the MTT would be reached by 2027.

353

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

361

362 Figure 5 – Minimun Technological Threshold for the Two- and the Seven-Variable
363 Scenarios.

364

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

366 The results presented above were obtained by adopting 75% recovery efficiency
367 throughout the lifetime of the CESM landfill. The effect of recovery efficiency on the MTT
368 year of occurrence and on the SSE for the three scenarios was tested by varying it from
369 55% to 95% in increments of 10 percentage points. At each increment, a new optimization
370 was performed for each scenario. The results obtained are presented in Figure 6, which
371 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.

Figure 6 – MTT year of occurrence (a) and SSE (b) as a function of recovery efficiency.

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 *FDR* and *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 CH_4 generation for the Seven-Variable Scenario.

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

412 and 2012 (Figure 4). These variances can be attributed to a myriad of causes, including: re-
413 excavation and re-landfilling of waste, temporary difficulties with the gas or leachate
414 collection systems (such as defective wells), localized settlements, localized elevated
415 temperatures, etc. Consideration of variable recovery efficiency could account, at least in
416 part, for the operational variances; hence the interest in considering it in further works. As
417 shown in this study, these limitations did not seem to influence the fact that the Seven-
418 Variable Scenario was found to be the most appropriate scenario to estimate shutdown
419 time, despite the fact that its minimization error was not the lowest.

420

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426

427 ## REFERENCES

428 Baillargeon, A., Bisson, M., Blouin, V., Mercure, A., Séguin, M., Guimond, J.Y., 2006.
429 Characterization study of the wastes landfilled at CESM (in French: Étude de
430 caractérisation des chargements entrant au CESM). City of Montreal (Ville de Montreal),
431 Montreal, QC, p. 21.

De la Cruz, F.B., Barlaz, M.A., 2010. Estimation of waste component-specific landfill decay rates using laboratory-scale decomposition data. Environ. Sci. Technol. 44, 4722−4728.

Franzidis, J.P., Héroux, M., Nastev, M., Guy, C., 2008. Lateral Migration and Offsite Surface Emission of Landfill Gas at City of Montreal Landfill Site. Waste Management & Research 26, 121-131.

Héroux, M., 2008. Développement d'outils de gestion des biogaz produits par les lieux d'enfouissement sanitaire (in French. Translation of title: Development of Landfill Biogas Management Tools), Génie minéral. École Polytechnique de Montréal, Montreal, Quebec, p. 281.

Héroux, M., Guy, C., Millette, D., 2010. A Statistical Model for Landfill Surface Emissions. Journal of Air & Waste Management Association 60, 219-228.

IPCC, 2006. Guidelines for National Greenhouse Gas Inventories, in: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Hayama, Japan.

Lagos, D.A., 2014. Optimisation du modèle de génération de méthane du lieu d'enfouissement du complexe environnemental de Saint-Michel, CUFE. Université de Sherbrooke, Sherbrooke, p. 80.

RECYC-QUÉBEC, 2000. Bilan 2000 de la gestion des matières résiduelles au Québec, p. 30.

Spokas, K., Bogner, J., Chanton, J.P., Morcet, M., Aran, C., Graff, C., Golvan, Y.M.-L., Hebe, I., 2006. Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems? Waste Management 26, 516-525.

454 Spokas, K., Bogner, J., Corcoran, M., Walker, S., 2015. From California dreaming to
455 California data: Challenging historic models for landfi ll CH_4 emissions. Elementa: Science
456 of the Anthropocene 3, 16.
457 Thompson, S., Sawyer, J., Bonam, R., Valdivia, J.E., 2009. Building a better methane
458 generation model: Validating models with methane recovery rates from 35 Canadian
459 landfills. Waste Management 29, 2085-2091.
460 USEPA, 2005. Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide.
461 United States Environmental Protection Agency, Washington, D.C., p. 56.
462 Wang, X., Nagpure, A.S., DeCarolis, J.F., Barlaz, M.A., 2013. Using Observed Data to
463 Improve Estimated Methane Collection from Select U.S. Landfills. Environmental Science
464 and Technology 47, 3251-3257.
465 Wang, X., Padgett, J.M., De la Cruz, F.B., Barlaz, M.A., 2011. Wood Biodegradation in
466 Laboratory-Scale Landfills. Environ. Sci. Technol. 45, 6864-6871.
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List of Tables

		Type of Waste		Climate Zone*							
				Boreal and Temperate (MAT ≤ 20°C)				Tropical[1] (MAT > 20°C)			
				Dry (MAP/PET < 1)		Wet (MAP/PET > 1)		Dry (MAP < 1000 mm)		Moist and Wet (MAP ≥ 1000 mm)	
				Default	Range[2]	Default	Range[2]	Default	Range[2]	Default	Range[2]
	SDR	Slowly degrading waste	Paper/textiles waste	0.04	0.03[3,5] – 0.05[3,4]	0.06	0.05 – 0.07[3,5]	0.045	0.04 – 0.06	0.07	0.06 – 0.085
			Wood/ straw waste	0.02	0.01[3,4] – 0.03[6,7]	0.03	0.02 – 0.04	0.025	0.02 – 0.04	0.035	0.03 – 0.05
	FDR	Moderately degrading waste	Other (non – food) organic putrescible/ Garden and park waste	0.05	0.04 – 0.06	0.1	0.06 – 0.1[8]	0.065	0.05 – 0.08	0.17	0.15 – 0.2
		Rapidly degrading waste	Food waste/Sewage sludge	0.06	0.05 – 0.08	0.185[4]	0.1[3,4] – 0.2[9]	0.085	0.07 – 0.1	0.4	0.17 – 0.7[10]

Max = 0.085
Min = 0.03

Max = 0.7
Min = 0.15

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

		Optimization range for k (yr^{-1})	Optimization range for L_0 (m^3 CH_4 Mg^{-1})
Two-Variable Scenario		[0.030–0.700]	[21–241]
Six-Variable Scenario		[0.030–0.700]	[21–241]
Seven-Variable Scenario	*FDR*	[0.100–0.700]	[21–115]
	SDR	[0.030–0.085]	[105–241]

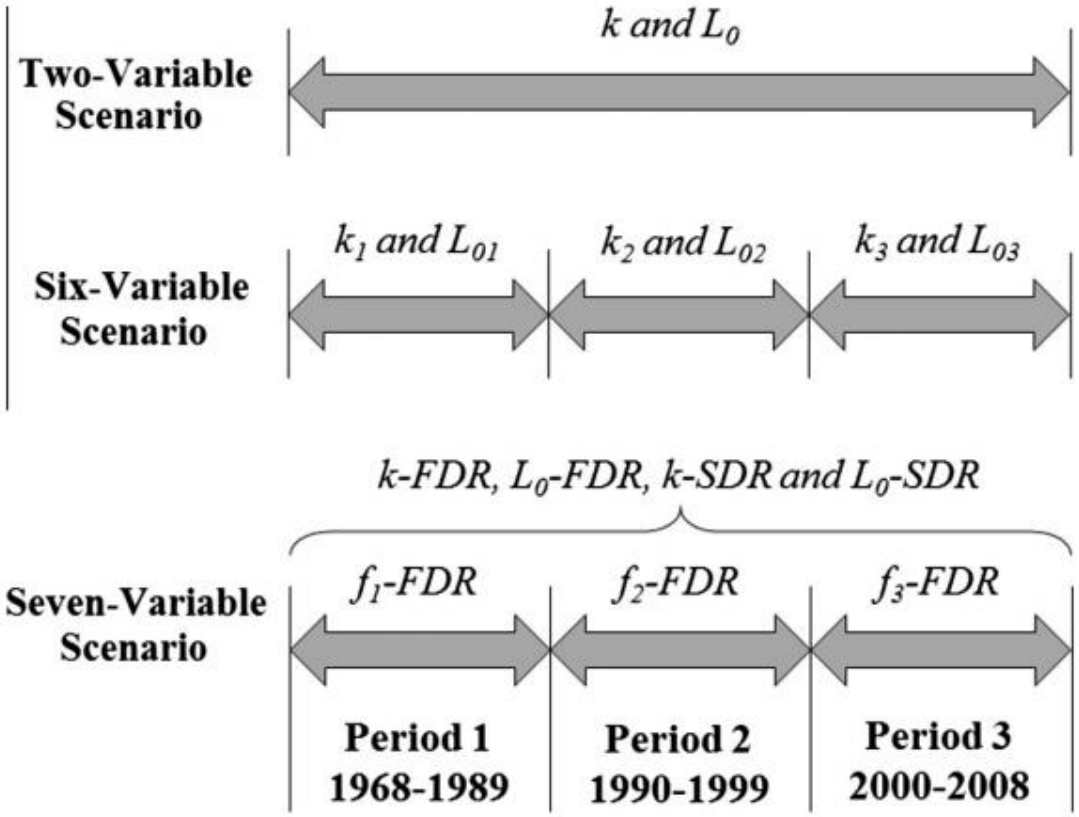
Table 2 - k and L_0 optimization ranges for the Two-, Six- and Seven-Variable Scenarios (Based on IPCC (2006) values).

Period	Optimization range for landfilled *FDR* fraction (%)
1: 1968–1989	[10–50]
2: 1990–1999	[30–70]
3: 2000–2008	[0–10]

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

495 **List of Figures**

496



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

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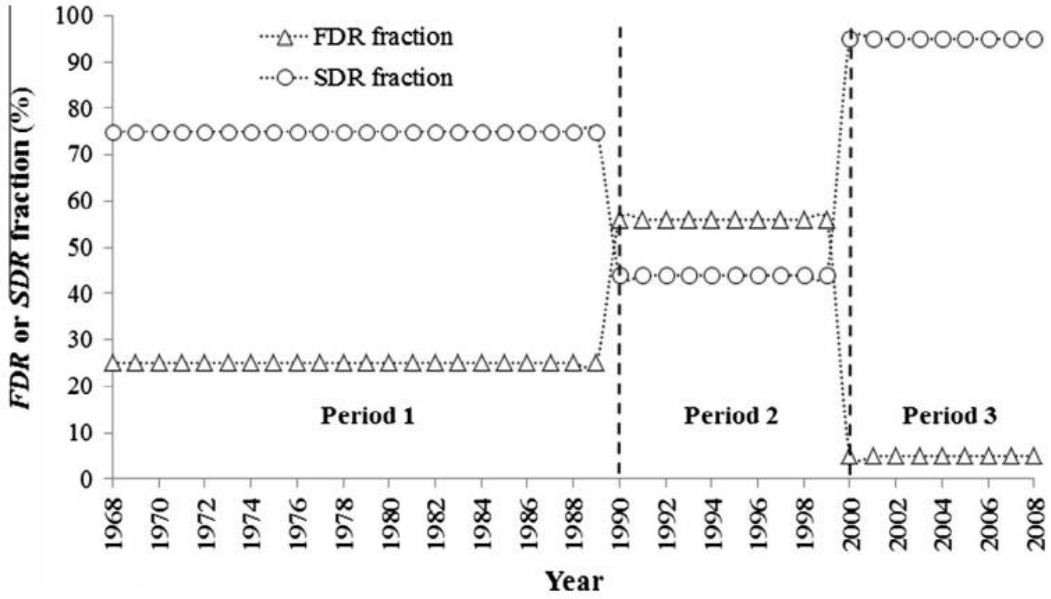


Figure **2** - Schematic representation of the evolution of estimated *FDR* and *SDR* fractions at CESM from opening (1968) to closure (2008).

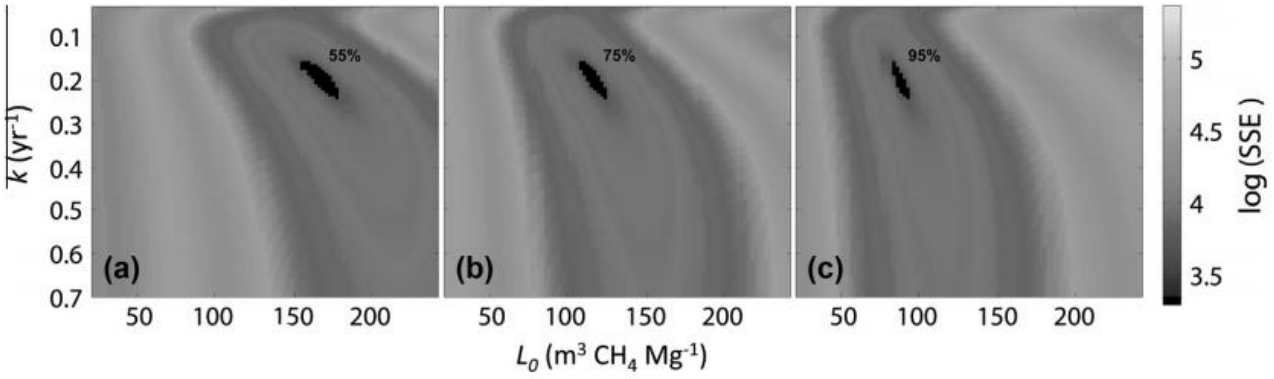
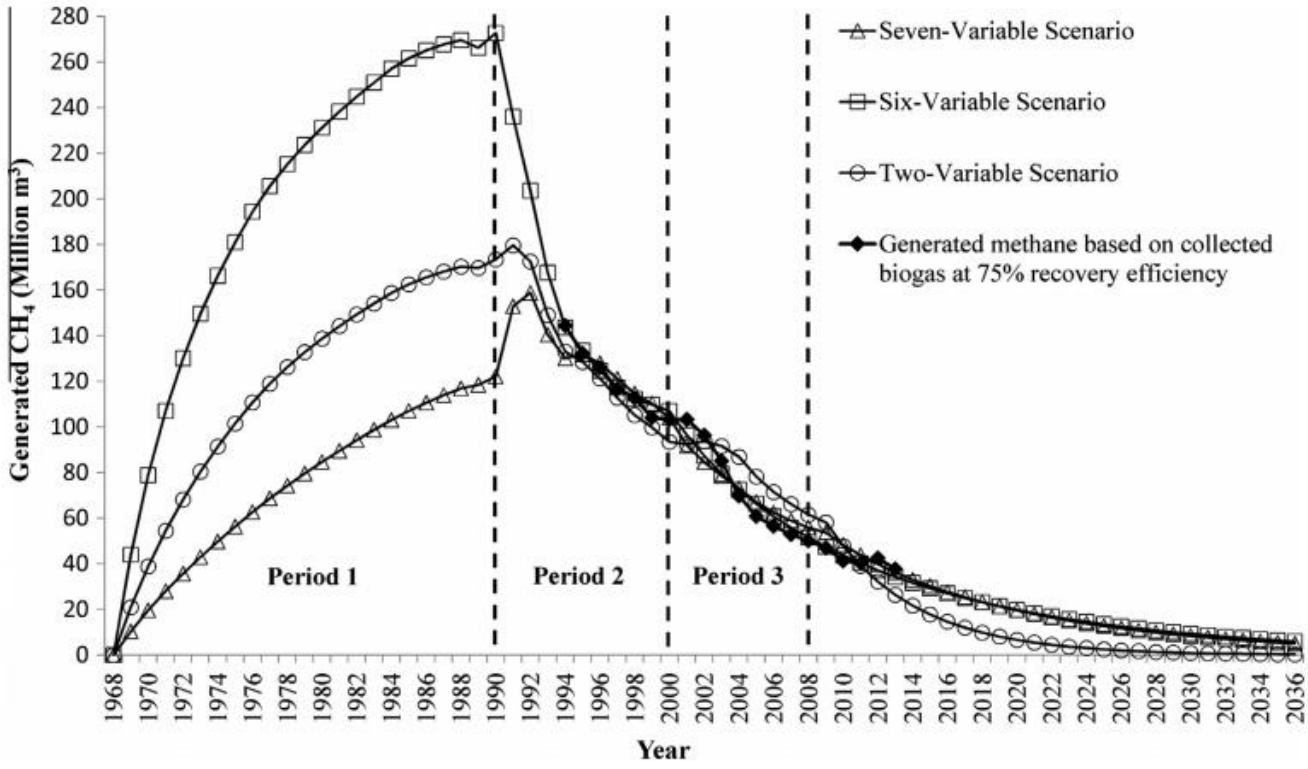


Figure 3 – Model-predicted errors for the Two-Variable Scenario as function of recovery efficiency.



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508 Figure 4 - Modeled CH_4 generation for the Two-, Six- and Seven-Variable Scenarios as

509 optimized after SSE minimization relative to measured CH_4 generation.

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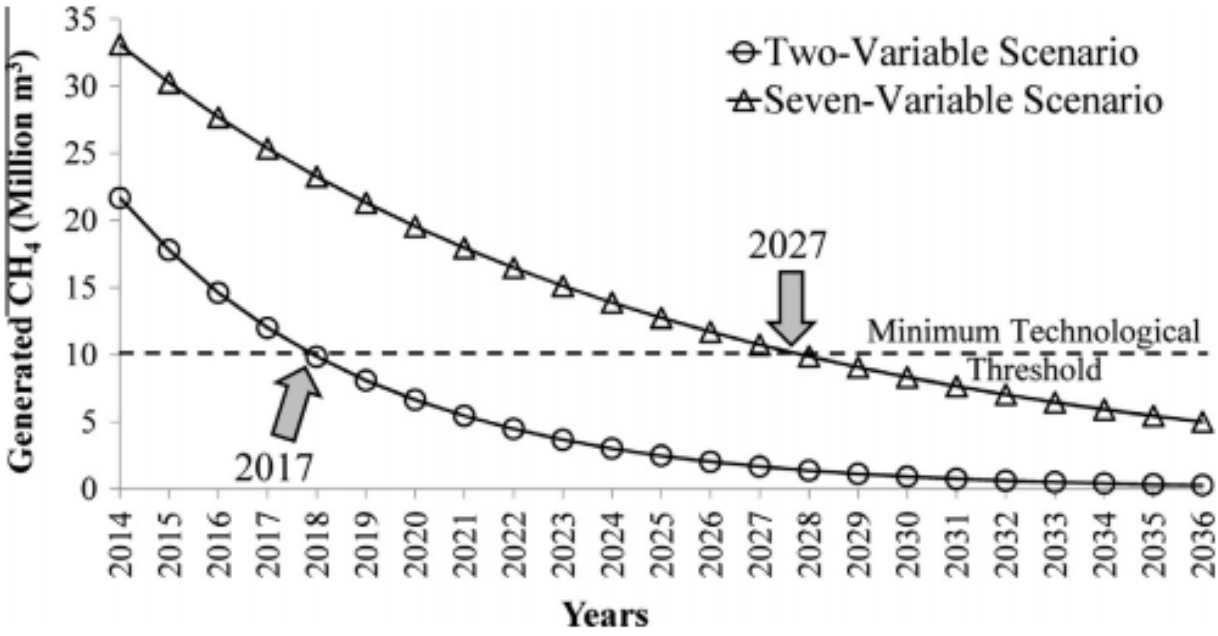

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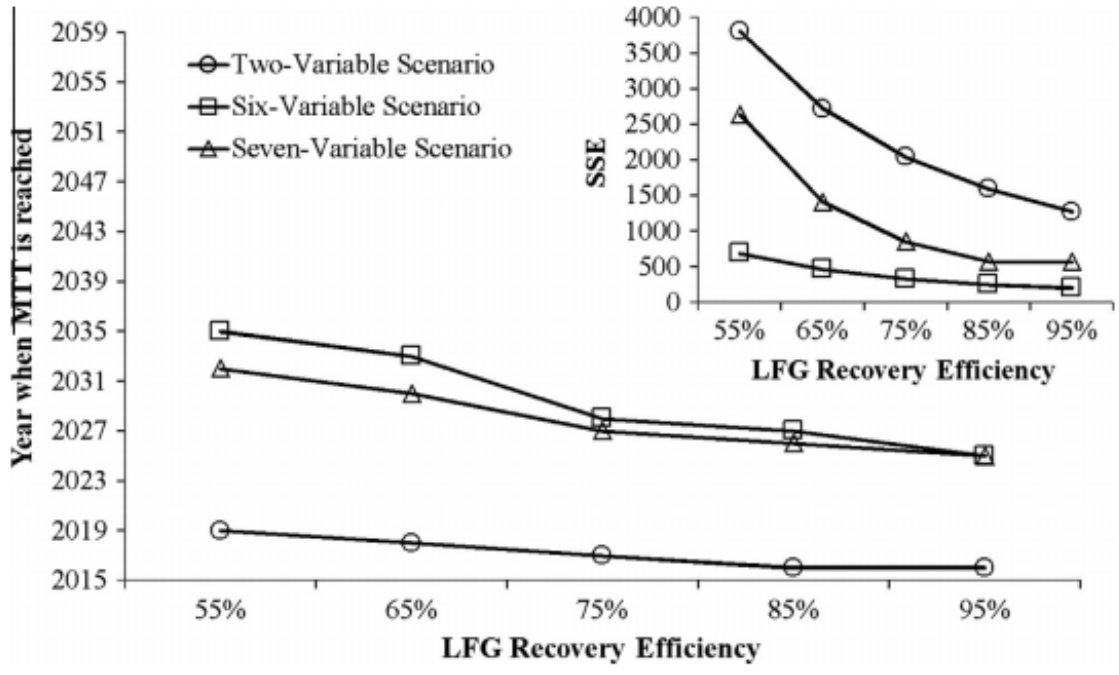
514 Figure 5 – Minimun Technological Threshold for the Two- and the Seven-Variable

515 Scenarios.



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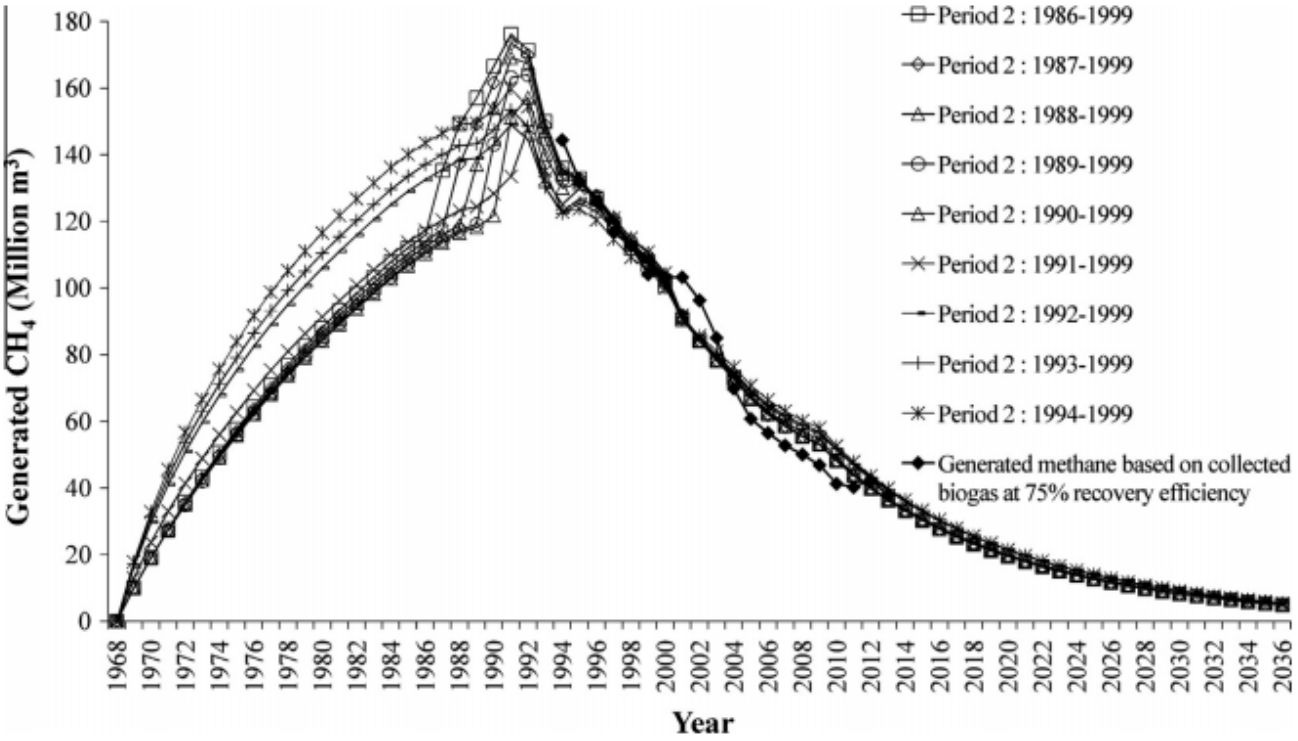
517 Figure 6 – MTT year of occurrence (a) and SSE (b) as a function of recovery efficiency.



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519 Figure **7** - Effect of the variation of the limit year between periods 1 and 2 on the

520 modeling of CH_4 generation for the Seven-Variable Scenario.