--FINAL REPORT--

LIFE CYCLE ASSESSMENT OF THE BIOREACTOR CONCEPT AND ENGINEERED LANDFILL FOR MUNICIPAL SOLID WASTE TREATMENT

Prepared for

ENVIRONMENT CANADA

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EXECUTIVE SUMMARY

Landfill is the most common disposal method for municipal solid waste in Canada. However, the engineered landfill used today requires large expanses of land and is not a permanent disposal mean in the sense that the waste remains in the landfill, generating gaseous and liquid emissions (landfill gas and leachate) over a very long period.

A new approach in landfill operation has arisen in the last few years which might reduce the burden associated with this activity: the bioreactor landfill. By controlling the physical and chemical conditions of the waste, essentially by keeping it moist using leachate recirculation, it is possible to accelerate the degradation, or stabilization, of the waste from an original degradation period of half a century or more to a matter of decades (10 to 20 years). This has a dual effect: 1) it reduces the temporal footprint, i.e. long-term emissions, of the landfilled waste since stabilized waste generates less emissions; 2) it reduces the need for land since it enables the treatment of more waste in the same landfill volume (waste is transformed to gas as it is degraded, thus reducing the space it occupies and providing additional capacity).

The goal of this study is to evaluate the environmental impacts related to the complete life cycle of these two landfill technologies. To achieve this goal, a Life Cycle Assessment (LCA) study comparing the potential environmental impacts associated with the proposed technologies was carried out. The study was not subjected to a critical review.

The principal function of the compared systems is to stabilize and manage a given amount of municipal solid waste (MSW). Since landfill gas may be used for heat or electrical energy production in the case of the bioreactor landfill, the production of heat and electrical energy was also included as a secondary function of the system through system expansion. This maintained the functional equivalence of the compared systems, i.e. they both have the same outputs (stabilized waste, electricity and heat). The deducted functional unit was defined as: the stabilization and management of 600 000 tonnes of MSW (300 000 tonnes/year of waste generated and disposed over a period of two years) and the production of 2.56×10^8 MJ[1] of electrical energy and 7.81×10^8 MJ[1] of heat energy.

The system boundaries included not only the landfill cell construction operation and associated emissions, but also the production processes and transport necessary to the implementation of these technologies. System boundaries were also expanded to include electricity and heat production processes (natural gas electrical power station and industrial boiler) to take into consideration the energy recovered from the collected landfill gas in the case of the bioreactor landfill.

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[1] Amount of energy produced equivalent to the maximum recoverable energy from the bioreactor landfill (based on the highest potential yield).

During the data collection, the first criterion to be considered was the data source (time, geography and technology criteria). North-American data, referring to average technologies and not older than 5 years was privileged. A non-detailed quality evaluation was carried out on the data. Three general conclusions were drawn from this evaluation: 1) data fulfilled the technological requirements; 2) data should be improved in the case of geographical representativeness and; 3) data was satisfactory in regards to temporal representativeness when considering that the technologies involved have not changed appreciably since the data was obtained (early 90's).

The most important assumptions made were the following:

- The waste occupies 25% less space in the bioreactor than in the engineered landfill since it is degraded and settled faster, freeing space for more waste in the same cell volume;

- The waste composition is the same for both options, thus the maximum landfill gas yield (Biochemical Methane Potential) obtainable is also the same. However, the effective landfill gas yield is only a fraction of this maximum since it is controlled by cell design and operation parameters. Since this fraction is not precisely known, a range of values was used to evaluate its influence on the assessment results; it was however assumed that this fraction was higher for the bioreactor than for the engineered landfill;

- The post-closure monitoring period, during which both leachate and landfill gas are collected, is of 30 years for both options. After this period, all activities on the site stop;

- The CO_2 produced from the waste is biogenic and, as such, was not considered in the greenhouse gases inventory (Global Warming Potential);

- Since not all of the potential landfill gas is produced, the carbon contained in this un-emitted fraction is stored in the remaining waste and the CO_2 that would have been produced from this carbon, is removed from the atmosphere and the carbon cycle and represents an environmental credit.

Data compilation and impact assessment were accomplished using the SimaPro 5 LCA software program. The Life Cycle Impact Assessment (LCIA) method used was the EDIP (Environmental Design of Industrial Products) method included in the software and the analysis was done on characterized results; normalization and weighting of these results, which are facultative, relative and rather subjective (based on geographically biased reference values and the interested parties value-choices) steps of impact assessment (ISO 14 042, 2000), were not carried out. The EDIP method follows a problem-oriented approach and takes into account different impact categories. The method does not consider noise, odours nor land use.

The methodology used to build the inventories of the systems and evaluate the potential environmental impacts was consistent throughout this study and allows for the comparison of the two options.

The engineered landfill requires more materials; energy inputs via the non-road equipment used and supplemented energy from external processes (natural gas electrical power station and industrial boiler) to achieve the same performance as the bioreactor landfill. The raw material inputs, solid waste outputs and potential environmental impacts associated with the emissions from the systems (presented in the following tables) are also greater for the engineered landfill option (on average, 126, 182 and 185% that of the bioreactor respectively). From these results, the bioreactor landfill can be identified as the option presenting the least impacts.

Material and Energy Inputs and Solid Waste Outputs for the Engineered and Bioreactor Landfills

Input/Output	Unit	Engineered landfill	Bioreactor Landfill
Materials	kg	1,42E+8	1,26E+8
Raw Materials	kg	2,20E+8	1,75E+8
Energy (non-road equipment)	MJ	2,60E+6	2,15E+6
Energy (electricity)	MJ	2,56E+8	1,50E+8
Energy (heat)	MJ	7,81E+8	4,55E+8
Solid Wastes	kg	4,42E+6	2,44E+6

The impact assessment identified the supplemented energy production as the dominant life cycle stage for both options (its average contribution to the impact indicator evaluated for each category considered is of 61% for the engineered landfill and 63% for the bioreactor), followed by the treatment and fugitive release of landfill gas (their contribution is of 33% and 32% for the engineered landfill and the bioreactor, respectively). This would tend to explain the advantage of the bioreactor option since, for that system, 1) energy is recovered from the collected landfill gas (1,07E+8 MJ of electricity and 4,32E+8 MJ of heat) and this reduces the need for external energy and 2) landfill gas is produced at a greater rate, reducing the amount directly released to the atmosphere after the end of the post-closure monitoring period, the methane it contains (a potent greenhouse gas) being no longer destroyed (in fact the end of the study period is reached before the end of the extraction of the landfill gas).

Impact Indicator Results for the Engineered and Bioreactor Landfills

Scale	Environmental Impact Category	Unit	Engineered landfill	Bioreactor Landfill
Global	Global Warming Potential (GWP)	g CO_2 eq.	1,98E+11	8,01E+10
	Ozone Depletion Potential (ODP)	g CFC11 eq.	1,34E+02	7,07E+01
Regional	Acidification Potential (AP)	g SO_2 eq.	1,67E+09	1,05E+09
	Eutrophication Potential (EP)	g NO_3 eq.	5,46E+08	4,20E+08
	Photochemical Ozone Creation Potential (POCP)	g C_2H_4 eq.	5,82E+07	2,46E+07
Regional/ Local	Ecotoxicological Impacts			
	– Ecotoxicity – Water, Chronic (ETWC)	m^3 water/g	1,18E+10	6,82E+09
	– Ecotoxicity – Water, Acute (ETWA)	m^3 water/g	1,19E+09	6,80E+08
	– Ecotoxicity – Soil, Chronic (ETSC)	m^3 soil/g	6,65E+06	3,53E+06
Local	ToxicoIogical Impacts (Human)			
	– Human Toxicity – Air (HTA)	m^3 air/g	2,87E+12	1,39E+12
	– Human Toxicity – Water (HTW)	m^3 water/g	2,83E+08	1,66E+08
	– Human Toxicity – Soil (HTS)	m^3 soil/g	3,24E+06	1,42E+06

Time constraints and lack of information led to the exclusion of several life cycle stages and unit processes. However, it is expected that the excluded leachate and landfill gas collection processes (essentially the energy used by the pumps and compressors) and the landfill gas treatment processes prior to the energy recovery in the case of the bioreactor (dehydrators, compressors and pipeline transport) would have had a negligible influence on the results had it been possible to quantify them since they involve very small quantities of materials and energy compared to the rest of the systems. The other excluded elements involved processes either unique to the engineered landfill, i.e. leachate treatment sludge management, or that would have had greater material and energy demands and associated emissions for that option, since they are proportional to the volume of the cell. They would have therefore generated greater environmental impacts for that option and would have lead to the same conclusion in favour of the bioreactor.

Certain considerations limit however the value of the above conclusions and are the basis of recommendations which would improve the validity of the results of this LCA study.

Finally, the results of this comparative study should not be taken out of this context and used as an absolute evaluation of the environmental impacts associated with either one of the options.

SOMMAIRE EXÉCUTIF

L'enfouissement est le mode d'élimination des matières résiduelles municipales le plus courant au Canada. Les lieux d'enfouissement sanitaire (LES) utilisés aujourd'hui nécessitent par contre de grands espaces et ne peuvent être considérés comme un moyen d'élimination définitif puisqu'ils peuvent générer des émissions (lixiviat et biogaz) sur une très longue période.

Une nouvelle approche, qui pourrait réduire les problèmes liés à l'enfouissement, a été développée au cours des dernières années : le bioréacteur. En contrôlant les conditions physico-chimiques des matières enfouies, essentiellement en les maintenant humides par la recirculation du lixiviat, il est possible d'accélérer le processus de dégradation, ou de stabilisation, des déchets d'une durée initiale de 50 ans ou plus à une période de 10 à 20 ans. Cette réduction du temps de dégradation a un double effet : 1) elle réduit l'empreinte temporelle des matières enfouies, i.e. leurs émissions à long terme, puisqu'elles génèrent moins d'émissions lorsque stabilisées, 2) elle réduit l'espace nécessaire puisqu'elle permet de traiter plus de déchets dans un même volume de cellule d'enfouissement (les déchets sont transformés en gaz durant leur dégradation, ce qui réduit le volume occupé et procure une capacité additionnelle).

L'objectif de l'étude est d'évaluer les impacts environnementaux associés au cycle de vie complet de ces deux technologies d'enfouissement. Afin d'atteindre cet objectif, une analyse du cycle de vie (ACV) comparative des impacts environnementaux potentiellement liés aux deux technologies a été réalisée. Cette étude n'a fait l'objet d'aucune revue critique.

La fonction principale des systèmes comparés est la stabilisation et la gestion d'une quantité donnée de matières résiduelles municipales. Puisque dans le cas du bioréacteur le biogaz peut être valorisé énergétiquement en électricité ou en chaleur, la production d'électricité et de chaleur doit être considérée en tant que fonction secondaire par l'expansion des frontières des systèmes. Ceci permet l'équivalence fonctionnelle des systèmes comparés, i.e. ils ont les mêmes sortants (déchets stabilisés, électricité et chaleur). À partir de ces considérations, l'unité fonctionnelle est définie comme : la stabilisation de 600 000 tonnes de matières résiduelles municipales (300 000 tonnes/année générées sur une période de 2 ans) et la production de 2.56×10^8 MJ[1] d'électricité et de 7.81×10^8 MJ[1] de chaleur.

Les frontières des systèmes incluent la construction de la cellule d'enfouissement, son opération et les émissions associées à ces activités, mais aussi les procédés de production (production des matériaux utilisés) et les transports nécessaires à l'implantation des technologies comparées. Les frontières ont aussi été étendues pour inclure les procédés de production d'électricité et de chaleur (centrale électrique et chaudière au gaz naturel)

[1] Quantité d'énergie produite équivalente à la quantité maximale d'énergie récupérable du bioréacteur (basée sur le rendement maximal de biogaz)

afin de considérer la valorisation énergétique du biogaz collecté dans le cas du bioréacteur.

Durant la phase de collecte des données, le premier critère considéré était la source de la donnée (critères temporels, géographique et technologique). Les données nord américaines, correspondant à des moyennes de technologies et n'ayant pas plus de 5 ans ont été privilégiées. Ces données ont de plus fait l'objet d'une évaluation qualitative non exhaustive. Trois conclusions générales ont été tirées de cette évaluation : 1) les données respectent le critère technologique ; 2) les données devraient être améliorées du point de vue de leur représentativité géographique ; et 3) les données sont satisfaisantes du point de vue de leur représentativité temporelle, en considérant que les technologies impliquées n'ont pas changé de façon appréciable depuis l'obtention des données (début 1990).

Les principales hypothèses posées sont les suivantes :

- Les déchets occupent 25% moins d'espace dans le bioréacteur que dans le LES puisqu'ils s'y dégradent et s'y tassent plus rapidement, permettant l'enfouissement d'une plus grande quantité de déchets dans un même volume de cellule ;

- La composition des déchets est la même pour les deux options, le rendement potentiel maximal en biogaz est donc le même. Par contre, le rendement réel en biogaz est seulement une fraction de ce maximum puisqu'il est soumis aux paramètres de conception et d'opération de la cellule. Puisque cette fraction n'est pas connue de façon précise, une plage de valeur a été utilisée pour évaluer son influence sur les résultats de l'étude ; la plage utilisée dans le cas du bioréacteur a par contre été, par hypothèse, établie comme étant supérieure à celle pour le LES ;

- La période de surveillance post-fermeture, durant laquelle le lixiviat et le biogaz sont collectés, est de 30 ans pour les deux options. Après cette période, toutes les activités sur le site prennent fin ;

- Le CO_2 produit à partir des matières résiduelles enfouies est d'origine biologique et n'a donc pas été considéré dans l'inventaire des gaz à effet de serre (Potentiel de réchauffement global) ;

- Puisque ce n'est pas tout le biogaz potentiel qui est effectivement produit, le carbone contenu dans la fraction non émise est stocké, i.e. séquestré, dans les déchets restants dans la cellule d'enfouissement et le CO_2 qui aurait été produit à partir de ce carbone est retiré de l'atmosphère et du cycle biogéochimique du carbone et représente un crédit environnemental.

La compilation des données et l'évaluation des impacts environnementaux potentiels ont été effectuées au moyen du logiciel ACV SimaPro 5. La méthode d'évaluation des impacts du cycle de vie (ÉICV) utilisée est la méthode EDIP (*Environmental Design of Industrial Products*) comprise dans le logiciel, et l'analyse a été effectuée à partir des résultats caractérisés i.e. les étapes de normalisation et de pondération des ces résultats n'ont pas été réalisées. Ces dernières constituent en effet des étapes facultatives, relatives et plutôt subjectives, puisque basées sur des valeurs de référence biaisées d'un point de vue géographique, et sur les choix de valeurs des parties intéressées (ISO 14 042, 2000). La méthode EDIP suit une approche orientée sur les problèmes et considère plusieurs catégories d'impacts. Elle ne considère toutefois pas le bruit, les odeurs et l'utilisation des terres.

La méthodologie utilisée lors de l'élaboration de l'inventaire des systèmes et l'évaluation des impacts environnementaux potentiels a été uniforme à chacune des phases de l'étude, ce qui permet la comparaison des deux options.

Afin d'avoir la même performance que le bioréacteur, le LES requiert plus de matériaux et d'énergie via les divers équipements hors route et les procédés de production externes (énergie supplémentaire fournie par la centrale électrique et la chaudière au gaz naturel). Les besoins en matières premières, les déchets solides produits et les impacts environnementaux potentiels associés aux émissions des systèmes (présentés dans les tableaux suivants) sont aussi plus importants pour le LES (en moyenne, 126, 182 et 185% ceux du bioréacteur respectivement).

Besoins en matériaux et en énergie et déchets solides générés pour le lieu d'enfouissement sanitaire (LES) et le bioréacteur

Entrants/sortants	Unité	LES	Bioréacteur
Matériaux	kg	1,42E+8	1,26E+8
Matières premières	kg	2,20E+8	1,75E+8
Énergie (équipements hors route)	MJ	2,60E+6	2,15E+6
Énergie (Électricité)	MJ	2,56E+8	1,50E+8
Énergie (Chaleur)	MJ	7,81E+8	4,55E+8
Déchets solides	kg	4,42E+6	2,44E+6

L'évaluation des impacts a identifié la production supplémentaire d'énergie comme la phase du cycle de vie dominante pour les deux options (sa contribution moyenne aux impacts évalués pour chaque catégorie considérée est de 61% pour le LES et de 63% pour le bioréacteur), suivi par le traitement et les émissions fugitives de biogaz (leur contribution est de 33% et de 32% pour le LES et le bioréacteur respectivement). Ceci tend à expliquer les impacts inférieurs liés au bioréacteur puisque : 1) le biogaz collecté est valorisé énergétiquement (pour une production de 1,07E+8 MJ d'électricité et de 4,32E+8 MJ de chaleur) ce qui réduit les besoins en énergie produite par des procédés externes ; et 2) le biogaz est produit plus rapidement, réduisant la quantité directement émise à l'atmosphère après la fin de la période de surveillance post-fermeture, le méthane qu'il contient (un gaz à effet de serre puissant) n'étant alors plus détruit (en fait, la frontière temporelle de l'étude est atteinte avant la fin de l'extraction du biogaz).

Résultats d'indicateurs d'impact pour le lieu d'enfouissement sanitaire (LES) et le bioréacteur

Échelle	Impact environnemental	Unité	LES	Bioréacteur
Globale	Réchauffement global	g CO_2 eq.	1,98E+11	8,01E+10
	Diminution de la couche d'ozone	g CFC11 eq.	1,34E+02	7,07E+01
Régionale	Acidification	g SO_2 eq.	1,67E+09	1,05E+09
	Eutrophisation	g NO_3 eq.	5,46E+08	4,20E+08
	Formation d'ozone photochimique	g C_2H_4 eq.	5,82E+07	2,46E+07
Régionale/ Locale	Impacts écotoxiques			
	– Écotoxicité – Eau, Chronique	m^3 eau/g	1,18E+10	6,82E+09
	– Écotoxicité – Eau, Aiguë	m^3 eau/g	1,19E+09	6,80E+08
	– Écotoxicité – Sol, Chronique	m^3 sol/g	6,65E+06	3,53E+06
Locale	Impacts toxiques (population humaine)			
	– Toxicité – Air	m^3 air/g	2,87E+12	1,39E+12
	– Toxicité – Eau	m^3 eau/g	2,83E+08	1,66E+08
	– Toxicité – Sol	m^3 sol/g	3,24E+06	1,42E+06

Le manque de temps et d'information a mené à l'exclusion de plusieurs phases du cycle de vie et processus élémentaires. Cependant, il est considéré que les processus exclus concernant la collecte du lixiviat et du biogaz (essentiellement l'énergie utilisée par les pompes et les compresseurs) et le traitement du biogaz avant sa valorisation énergétique dans le cas du bioréacteur (déshumidificateurs, compresseurs et transport par pipeline) auraient eu une influence négligeable sur les résultats s'il avait été possible de les quantifier, puisqu'ils impliquent de faibles quantités de matériaux et d'énergie par rapport au reste des systèmes. Les autres éléments exclus impliquent des processus uniques au LES, i.e. la gestion des boues de traitement du lixiviat, ou qui auraient des besoins en matériaux et en énergie et des émissions associées supérieurs pour cette option puisqu'ils sont proportionnels au volume de la cellule d'enfouissement. Ils auraient ainsi généré des impacts plus importants pour cette option et mené aux mêmes conclusions favorisant le bioréacteur.

Certaines considérations limitent toutefois la valeur des conclusions présentées ci-dessus. Ces considérations sont à la base de recommandations qui amélioreraient la validité des résultats de cette ACV.

Finalement, les résultats de cette étude comparative ne doivent pas être pris hors de leur contexte et utilisés comme une évaluation objective des impacts environnementaux associés à l'une ou l'autre des options.

TABLE OF CONTENTS

PROJECT TEAM .... **III**

EXECUTIVE SUMMARY .... **V**

SOMMAIRE EXÉCUTIF .... **IX**

TABLE OF CONTENTS .... **XIII**

LIST OF TABLES .... **XV**

LIST OF FIGURES .... **XVI**

ACRONYMS AND ABBREVIATIONS .... **XVII**

1. GENERAL INTRODUCTION **1**

1.1. PROBLEM 1
1.2. OBJECTIVE 2
1.3. METHODOLOGY 2
1.3.1. *Goal and Scope Definition* *3*
1.3.2. *Inventory Analysis* *3*
1.3.3. *Impact Assessment* *3*
1.3.4. *Interpretation* *4*

2. LCA PHASE I: GOAL AND SCOPE DEFINITION **5**

2.1. GOAL OF THE STUDY 5
2.1.1. *Purpose of the Study* *5*
2.1.2. *Context of the Study* *5*
2.1.3. *Intended Audience* *5*
2.2. SCOPE OF THE STUDY 6
2.2.1. *Function, Functional Unit and Reference Flows* *6*
2.2.2. *System Boundaries and Description* *7*
2.2.3. *Data Category Description* *14*
2.2.4. *Data Quality Requirements* *16*
2.2.5. *Allocation Rules* *17*
2.2.6. *General Assumptions* *18*
2.2.7. *Environmental Impact Evaluation* *19*
2.2.8. *Equivalence of the Compared Systems* *21*
2.2.9. *Interpretation Methods* *22*
2.2.10. *Critical Review* *22*
2.2.11. *Limits of the Study* *22*
2.2.12. *Final Report Format* *23*

3. LCA PHASE II: INVENTORY ANALYSIS **24**

3.1. DATA COLLECTION METHODOLOGY 24
3.2. DESCRIPTION OF THE PRODUCT SYSTEMS 24
3.2.1. *Cell Excavation and Berm Construction* *24*
3.2.2. *Liner and Leachate Collection Systems* *24*
3.2.3. *Leachate Treatment System (Engineered landfill)* *25*
3.2.4. *Leachate Recirculation and Landfill Gas Collection System (Bioreactor Landfill)* *25*
3.2.5. *Final Cover* *26*

3.2.6. *Landfill Gas Collection System (Engineered landfill)* 26
3.2.7. *Leachate Treatment and Emissions* 26
3.2.8. *Landfill Gas Treatment and Emissions* 27
3.2.9. *Energy Production* 27
3.3. DATA SOURCES AND CATEGORIES 27
3.3.1. *Materials* 28
3.3.2. *Non-Road Equipment* 28
3.3.3. *Transportation* 28
3.4. ASSUMPTIONS AND CALCULATION PROCEDURES 29
3.4.1. *Design Calculations* 29
3.4.2. *Materials* 30
3.4.3. *Non-Road Equipment* 31
3.4.4. *Transportation* 31
3.4.5. *Leachate* 32
3.4.6. *Landfill Gas* 35
3.5. DATA VALIDATION 40
3.5.1. *Mass Balance Verification* 40
3.5.2. *Data Quality Evaluation* 41
3.5.3. *Missing Data Considerations* 41
3.6. INVENTORY RESULTS 41
3.6.1. *Raw Materials* 43
3.6.2. *Emissions to air* 43
3.6.3. *Emissions to Water* 44
3.6.4. *Solid Emissions* 44
3.7. INVENTORY ANALYSIS LIMITATIONS 51
3.7.1. *General Data Quality Evaluation* 51
3.7.2. *Accuracy of the Results* 53

4. LCA PHASE III: IMPACT ASSESSMENT 54

4.1. CLASSIFICATION AND CHARACTERIZATION 54
4.1.1. *Life Cycle Impact Assessment Profiles* 55
4.2. ASSESSMENT OF DATA GAPS 63

5. LCA PHASE IV: RESULT INTERPRETATION 65

5.1. IDENTIFICATION OF SIGNIFICANT ISSUES 65
5.2. RESULT VERIFICATION 67
5.2.1. *Evaluation of Completeness* 68
5.2.2. *Evaluation of Consistency* 68
5.3. CONCLUSIONS AND RECOMMENDATIONS 69
5.3.1. *Conclusions* 69
5.3.2. *Recommendations* 70

REFERENCES 73

APPENDICES 75

LIST OF TABLES

TABLE 1-1: IMPACT CATEGORIES RECOMMENDED BY ISO (JENSEN *ET AL.*, 1997) 4
TABLE 2-1: ENVIRONMENTAL IMPACT CATEGORIES CONSIDERED BY THE EDIP METHOD (WENZEL ET AL., 1997) 20
TABLE 3-1: DATA SOURCES AND CATEGORIES 28
TABLE 3-2: MATERIAL SPECIFICATIONS CONSIDERED 30
TABLE 3-3: LEACHATE PRODUCTION PARAMETERS 32
TABLE 3-4: LEACHATE COMPOSITION FOR THE ENGINEERED LANDFILL (SICH AND BARLAZ, 2000) 33
TABLE 3-5: LEACHATE COMPOSITION FOR THE BIOREACTOR LANDFILL (SICH AND BARLAZ, 2000) 34
TABLE 3-6: LEACHATE TREATMENT EFFICIENCY FOR THE ENGINEERED LANDFILL SYSTEM (SICH AND BARLAZ, 2000) 34
TABLE 3-7: SWANA LANDFILL GAS PRODUCTION MODEL PARAMETERS (SICH AND BARLAZ, 2000) 36
TABLE 3-8: WASTE COMPOSITION (CHAMARD ET AL., 2000) 36
TABLE 3-9: SPECIFIC WASTE COMPONENT METHANE YIELD AND MOISTURE CONTENT (SICH AND BARLAZ, 2000; U.S. EPA, 2002) 37
TABLE 3-10: LANDFILL GAS COMPOSITION (SICH AND BARLAZ, 2000) 38
TABLE 3-11: LANDFILL GAS COLLECTION SYSTEM EFFICIENCY 38
TABLE 3-12: LANDFILL GAS TREATMENT METHOD DESTRUCTION EFFICIENCIES AND EMISSION FACTORS (SOIL OXIDATION IS ALSO PRESENTED) (SICH AND BARLAZ, 2000) 39
TABLE 3-13: DESIGN CALCULATION RESULTS FOR THE ENGINEERED AND BIOREACTOR LANDFILLS 42
TABLE 3-14: INVENTORY RESULTS SUMMARY – ENGINEERED LANDFILL 45
TABLE 3-15: INVENTORY RESULTS SUMMARY – BIOREACTOR LANDILL 45
TABLE 4-1: LCIA PROFILE – ENGINEERED LANDFILL 57
TABLE 4-2: LCIA PROFILE – BIOREACTOR LANDFILL 58
TABLE 5-1: MATERIAL AND ENERGY REQUIREMENTS FOR THE TWO LANDFILL OPTIONS 66

LIST OF FIGURES

FIGURE 1-1: LCA FRAMEWORK (ISO 14 040, 1997).....2
FIGURE 2-1: FUNCTIONAL EQUIVALENCE OF COMPARED PRODUCT SYSTEMS. 7
FIGURE 2-2: INITIAL SYSTEM BOUNDARIES.....8
FIGURE 2-3: LIFE CYCLE STAGES CONSIDERED. 9
FIGURE 2-4: LIFE CYCLE STAGES CONSIDERED (DETAILS). 11
FIGURE 3-1: ABSOLUTE CONTRIBUTION OF MASS FLOWS FOR THE ENGINEERED LANDFILL, BY COMPARTMENTS AND LIFE CYCLE STAGES (SEE FIGURE 2-4), 40 & 70% LANDFILL GAS YIELD. 47
FIGURE 3-2: RELATIVE CONTRIBUTION OF MASS FLOWS FOR THE ENGINEERED LANDFILL, BY COMPARTMENTS AND LIFE CYCLE STAGES (SEE FIGURE 2-4), 40 & 70% LANDFILL GAS YIELD. 47
FIGURE 3-3: ABSOLUTE CONTRIBUTION OF MASS FLOWS FOR THE BIOREACTOR LANDFILL, BY COMPARTMENTS AND LIFE CYCLE STAGES (SEE FIGURE 2-4), 60 & 90% LANDFILL GAS YIELD, ICE AND BOILER.....49
FIGURE 3-4: RELATIVE CONTRIBUTION OF MASS FLOWS FOR THE BIOREACTOR LANDFILL, BY COMPARTMENTS AND LIFE CYCLE STAGES (SEE FIGURE 2-4), 60 & 90% LANDFILL GAS YIELD, ICE AND BOILER.....49
FIGURE 4-1: LCIA PROFILE FOR THE ENGINEERED LANDFILL, BY LIFE CYCLE STAGES (40 & 70% LANDFILL GAS YIELD). 59
FIGURE 4-2: LCIA PROFILE FOR THE BIREACTOR LANDFILL, BY LIFE CYCLE STAGES (60 & 90% LANDFILL GAS YIELD, ICE & BOILER). 61
FIGURE 5-1: RELATIVE SCORES OF THE IMPACT INDICATORS FOR THE TWO LANDFILL OPTIONS. 67

ACRONYMS AND ABBREVIATIONS

AP	Acidification Potential
BMP	Biochemical Methane Potential
BOD	Biological Oxygen Demand
CIRAIG	Interuniversity Reference Center for the Life Cycle Assessment, Management of Products, Processes and Services
COD	Chemical Oxygen Demand
CFC	Chlorofluorocarbon
EDIP	Environmental Design of Industrial Products
EF	Elementary Flow
EP	Eutrophication Potential
ETSC	Ecotoxicity Soil Chronic
ETWA	Ecotoxicity Water Acute
ETWC	Ecotoxicity Water Chronic
FML	Flexible Membrane Liner
GCL	Geosynthetic Clay Liner
GHG	Green House Gases
GWP	Global Warming Potential
HDPE	High Density Polyethylene
HTA	Human Toxicity Air
HTS	Human Toxicity Soil
HTW	Human Toxicity Water
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	MegaJoule
MSW	Municipal Solid Waste
ODP	Ozone Depletion Potential

POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
SWANA	Solid Waste Association of North America
TSS	Total Suspended Solids
UNECE	United Nations Economic Council for Europe
UNEP	United Nations Environment Programme
USEPA	United Nations Environmental Protection Agency
VOC	Volatile Organic Compounds
WMO	World Meteorological Organization

1. GENERAL INTRODUCTION

In September 2002, the Interuniversity Reference Center for the Life Cycle Assessment, Interpretation and Management of Products, Processes and Services (CIRAIG) of the École Polytechnique de Montréal submitted two research proposals for the life cycle assessment (LCA) of the bioreactor concept and engineered landfill for municipal solid waste treatment (Samson *et al.*, 2002a & 2002b). These proposals, consisting of two major components, were submitted to Intersan Inc. and Environment Canada. The components are 1) a preliminary phase, which includes the model development i.e. the first LCA phase consisting of the study's goal and scope definition and 2) the main phase of the study, which includes the three other LCA phases (i.e. the inventory analysis, the impact assessment and the interpretation of the results). The proposals were subsequently accepted by Intersan Inc. and Environment Canada.

In December 2002, a progress report was submitted to Intersan Inc. and Environment Canada, describing the first phase of the LCA (Samson *et al.*, 2002c).

This document is the final report of the project, which is divided into five parts: a general introduction and four sections corresponding to the four major phases of the project (defined below). General conclusions and recommendations are presented in the fourth LCA phase.

1.1. Problem

Our society is facing an incredible challenge in the management of the increasing amount of municipal solid waste it produces. Many management options are available, all following the 3 R-V principle, i.e. reduce, re-use, recycle and valorize but, eventually some waste has to be eliminated. To that effect the number of possibilities is greatly reduced; essentially the waste can be incinerated or placed in a landfill. The first option implies air emissions and public disfavour but has the advantage of dramatically reducing the volume of the material to be disposed of, only the remaining ashes have to be eliminated (generally in a landfill). The second option, the most common, requires large expanses of land and is not a permanent disposal mean in the sense that the waste remains in the landfill, generating emissions (landfill gas and leachate) over a very long period and possibly becoming a burden for future generations.

A new approach in landfill operation has arisen in the last few years which might reduce the burden associated with this activity: the bioreactor landfill. By controlling the physical and chemical conditions of the waste, essentially by keeping it moist using leachate recirculation, it is possible to accelerate the degradation, or stabilization, of the waste from an original degradation period of half a century or more to a matter of decades (10 to 20 years). This has a dual effect: 1) it reduces the temporal footprint, i.e. long-term emissions, of the landfilled waste since stabilized waste generates less emissions; 2) it reduces the need for land since it enables the treatment of more waste in the same landfill volume (waste is transformed to gas as it is degraded, thus reducing the space it occupies and providing additional capacity).

However, to be able to evaluate if this new option presents the best environmental profile it is necessary to conduct a thorough investigation of all aspects involved, i.e. to consider all the activities associated with the disposal of municipal solid waste (MSW) in a bioreactor. Life cycle assessment, by considering a system in its totality, from raw material acquisition to final disposal, can provide such information.

1.2. Objective

The present study aims to provide the basis to compare the two different MSW treatment types i.e. engineered landfills and bioreactor landfills. The life cycle assessment will allow the evaluation of the potential environmental impacts related to the complete life cycle of these two options, with the aim of identifying the most sustainable one.

1.3. Methodology

Life Cycle Assessment (LCA) is a tool that allows the evaluation of the environmental consequences of a product or an activity over its entire life cycle (cradle to grave analysis). It is therefore a holistic approach, which takes into account the extraction and processing of raw materials, the manufacturing process, the transport and distribution, the use and reuse of finished product, and the recycling and management of wastes.

This type of analysis implies the identification and the quantification of all entering and outgoing materials and energy, and the evaluation of potential impacts associated with these flows. Figure 1-1 presents the technical framework for LCA, as suggested by the International Organization for Standardization (ISO 14 040, 1997).

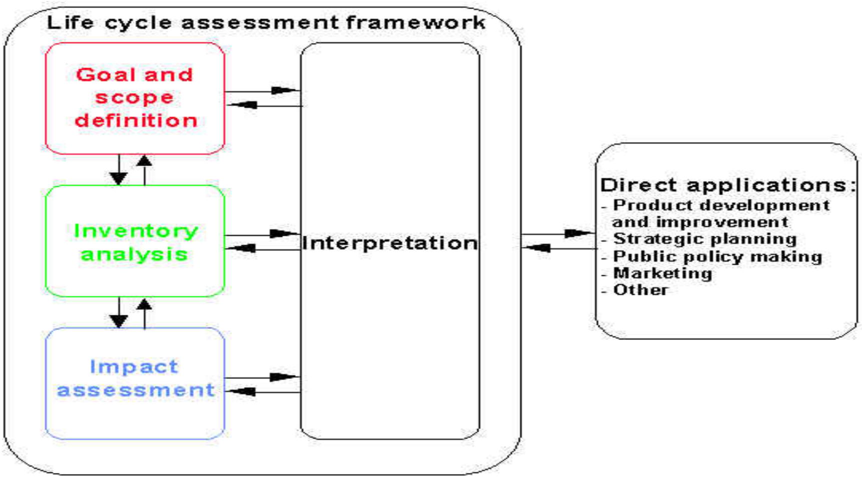

Figure 1-1: LCA Framework (ISO 14 040, 1997).

Thus, a complete LCA study consists of:

- Establishing the goal and scope of the study (Phase I);
- Compiling an inventory of relevant inputs and outputs of a system (Phase II);
- Evaluating the potential environmental impacts associated with these inputs and outputs (Phase III);
- Interpreting the results of the inventory and impact phases in relation to the goal and scope of the study (Phase IV).

It must be noted that an LCA study is an iterative process. Choices made during each of the LCA phases can be modified during the progress of the study, as new information is acquired.

1.3.1. *Goal and Scope Definition*

The first LCA phase consists in defining the goal and scope of the study, which deals with the identification of the parameters that will set the boundaries of the study, i.e. what will be considered in terms of the different unit processes that make up the technological system under study (technosphere) and the methods for evaluating their impacts on the environment.

The goal of the study includes the intended application and audience, and the reason for carrying out the study. The scope includes the establishment of the functional unit and boundaries (geographical, temporal and technological), the identification of requirements concerning data quality, as well as the presentation of assumptions and impact evaluation methods used.

1.3.2. *Inventory Analysis*

The second LCA phase, called life cycle inventory (LCI), is the quantification of elementary flows crossing the system boundaries. Data is collected, mass and energy inputs and outputs are calculated and the results are presented for each of the life cycle stages:

- Raw material acquisition and transformation;
- Production and assembling;
- Transport and distribution;
- Use;
- Waste disposal.

In order to ensure coherence and transparency of the study, it is important to have data quality information relating to data sources, data categories and level of aggregation.

1.3.3. *Impact Assessment*

The inventory phase allows the quantification of matter and energy flows associated with the system under study. According to the extent of the analysis and the complexity of the system, the quantity of data collected will be more or less significant. The use of this data can be difficult in practice, and it is therefore important to employ a method of interpretation of these results. This is the role of the life cycle impact assessment (LCIA) phase.

In order to evaluate the potential impact of the systems under study, ISO recommends considering 10 impact categories, which are presented in Table 1-1.

Table 1-1: Impact Categories Recommended by ISO (Jensen *et al.*, 1997)

Impact Scale	Impact Category
Global environmental impacts	Global warming potential Stratospheric ozone depletion
Regional environmental impacts	Acidification Eutrophication Smog
Local environmental impacts	Land use Ecotoxicological impacts Toxicological impacts
Other impacts	Abiotic resource depletion Biotic resource depletion

1.3.4. *Interpretation*

The last LCA phase consists in analyzing results, making conclusions, explaining the limits of the study and providing recommendations. This includes a summary of the results obtained and a verification of their conformity with the goal and scope of the study. Ideally, the interpretation is carried out in interaction with the three preceding LCA phases. For each potential management option, the LCA final results consist of:

- Material and energy consumption;
- Critical life cycle stages;
- Contribution to environmental impact categories.

The results also suggest better technological choices, and thus help to minimize economic losses.

2. LCA PHASE I: GOAL AND SCOPE DEFINITION

This section presents the first phase of the LCA process, which is the specification of the goal and scope of the study. Due to the iterative nature of the life cycle assessment process, some decisions previously made have been modified according to results observed at some iteration. Modifications carried out on the initial goal and scope definition (see progress report: Samson *et al.,* 2002c) is documented in Appendix A.

2.1. Goal of the Study

2.1.1. *Purpose of the Study*

The life cycle assessment aims to compare the potential environmental impacts associated with the disposal of MSW in two types of landfills, i.e. engineered landfills and bioreactor landfills. The ultimate intended application of the LCA results is to influence future decisions concerning MSW management.

As mentioned in the research proposals (Samson *et al.*, 2002a & 2002b), the purpose of the LCA described here is to provide a preliminary view of the actual situation in Canadian landfilling practices, using a generic hypothetical situation. Therefore, this LCA will simply allow the characterization of typical processes and the identification of the most damaging aspects of these processes, so that special attention could be paid to these during later studies or during the decision-making process concerning the disposal of MSW. A comparative LCA will thus be carried out on the two MSW disposal alternatives following the four phases recommended by ISO. However, for economic and practical reasons, the ISO standards will not be followed in an integral way. Such simplifications will affect the precision and applicability of the LCA results, but will permit the identification and, to a certain extent, the evaluation of impacts.

2.1.2. *Context of the Study*

Information on the environmental aspects of the two alternative waste treatment technologies, engineered and bioreactor landfills, is required in order to guide decisions concerning waste management. The life cycle assessment proposed (Samson *et al.*, 2002a & 2002b) will provide the basis to compare these two different MSW treatment types. The comparison will be made through the evaluation of the potential environmental impacts at the local, regional and global scale.

2.1.3. *Intended Audience*

The intended audience spans all decision makers regarding MSW management. The results of the study will be made public.

According to the ISO standards, this type of comparative study should be intended for strictly internal use by Environment Canada and Intersan Inc. The elements recommended by ISO for comparative LCA disclosed to the public are presented in the following paragraphs under the heading "recommendations for public disclosure of the LCA's results". The present study should therefore be revised according to these recommendations prior to public disclosure.

2.2. Scope of the Study

2.2.1. *Function, Functional Unit and Reference Flows*

2.2.1.1. Function

The function enables the identification of the performance properties of the product or activity under study. Compared product systems must be functionally equivalent (ISO 14 040, 1997).

The principal function of the compared systems is to stabilize and manage a given amount of municipal solid waste. Since landfill gas may be used for heat or electrical energy production, the production of heat and electrical energy is also included as a function of the system through the expansion of system boundaries. This ensures the equivalence of the system functions (Figure 2-1 shows that the equivalent systems have the same functional outputs compared to the non-equivalent ones).

In the case of the engineered landfill, the collected landfill gas is burned in a flare and no energy is recovered from the combustion; the model must then be supplemented with processes that would normally be mobilized for energy production since this option does not supply electrical or heat energy.

In the case of the bioreactor, the landfill gas can be used to produce one or the other forms of energy. Therefore, both situations have to be considered and for each, the system must be supplemented with the processes producing the other form of energy, i.e. heat when electricity recovery is considered and vice versa.

2.2.1.2. Functional Unit

The functional unit permits the quantification of the identified functions and the subsequent normalization of the LCI results. It must be defined with the goal and purpose of the study in mind. It must also be identical for all the systems under study so as to ensure their comparison (ISO 14 040, 1997).

In this case, the functional unit defined is the stabilization and management of 600 000 tonnes of MSW (300 000 tonnes/year of waste generated and disposed over a period of two years) and the production of 2.56×10^8 MJ[1] of electrical energy and 7.81×10^8 MJ[1] of heat energy.

2.2.1.3. Reference Flows

The reference flows allow one to link the performance of the option under study to the functional unit. The reference flows are one engineered landfill and one bioreactor landfill, both having a capacity of 600 000 tonnes.

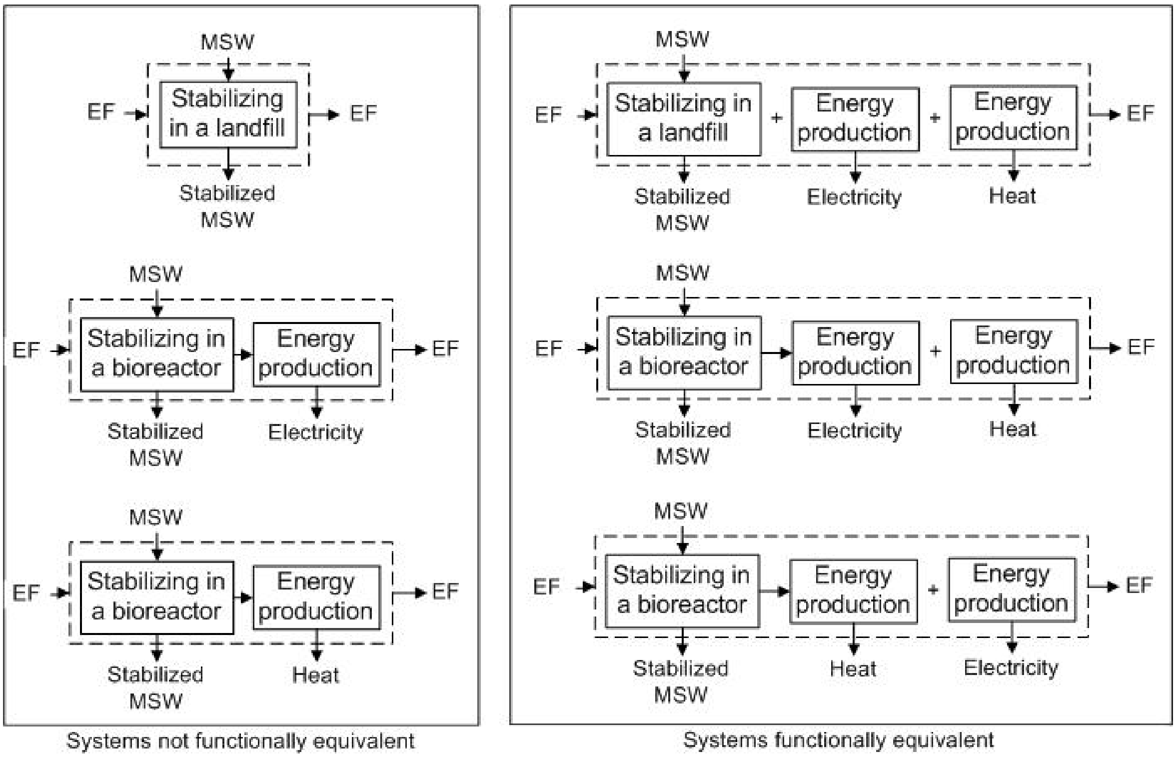

Figure 2-1: Functional Equivalence of Compared Product Systems.

2.2.2. *System Boundaries and Description*

2.2.2.1. Basic Rules for Setting the System Boundaries

The system boundaries determine 1) what unit processes and flows are to be considered in the life cycle assessment and 2) the frontier between the technosphere and the ecosphere.

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[1] Amount of energy produced equivalent to the maximum recoverable energy from the bioreactor landfill (based on the highest potential yield).

All the processes contributing above a specified threshold to mass or energy balances or to impact categories should be included (ISO 14 040, 1997). In a comparative LCA, it is particularly important to include the processes that significantly differentiate the systems (Guinée *et al.*, 2001). Since the scoping is done before the actual collection of LCI data, it should be noted that the initial boundaries may subsequently be refined.

The setting of the boundary between the technosphere and the ecosphere is necessary to know which flows are elementary (i.e. flows that are taken directly from or released directly into the environment, and therefore contribute to impact categories) and which flows are intermediate (i.e. flows from one unit process to another and that are used to determine the intensity of the modeled unit processes).

2.2.2.2. System Overview

The initial scope of the study is presented in Figure 2-2 within the context of a comprehensive waste management LCA.

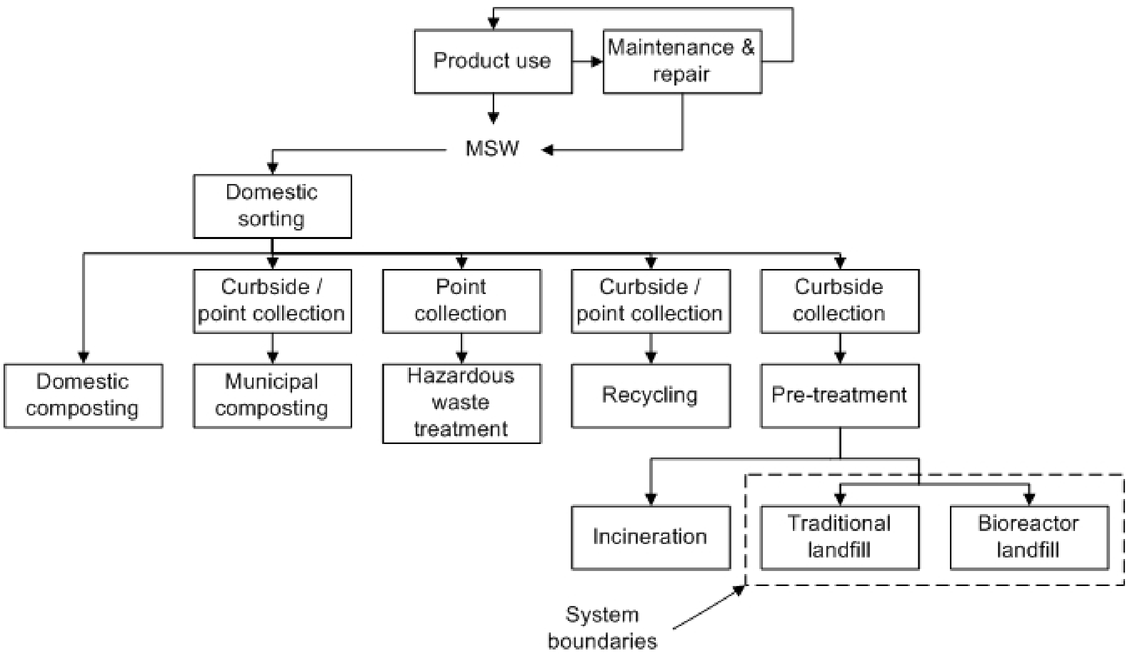

Figure 2-2: Initial System Boundaries.

Both the engineered and bioreactor landfill unit processes will be further detailed. In both, five life cycle stages are identified: site development, cell construction, pre-closure (daily) & closure operations, post-closure operations, leachate and landfill gas treatment and emissions (Figure 2-3).

As shown in this figure, since landfill gas can be recovered and used for electrical or heat energy production in the bioreactor option, the system must be expanded to include energy (electrical and heat) production processes. The chosen energy production processes are the natural gas electrical power station and the natural gas industrial boiler since LCAs aimed at decision-making use displaced (or marginal) technology, i.e. electricity generation from a landfill can be expected to reduce electricity production from fossil fuels (natural gas in this case), but not from hydroelectric dams.

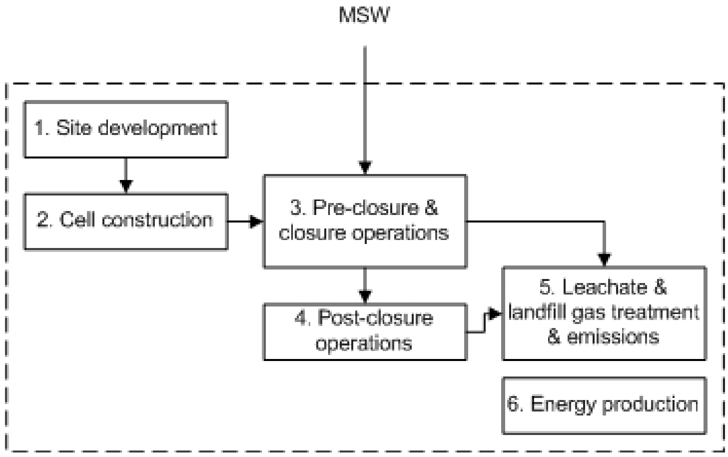

Figure 2-3: Life Cycle Stages Considered.

2.2.2.3. Geographical Boundaries

All landfilling and landfill gas energy recovery activities are assumed to take place in Canada, which represents a rather large area. As such, some of the data must reflect this variability (e.g. rainfall). For other processes tied to energy and material procurement, the unit processes can usually occur anywhere on the globe: when possible, the data used will best reflect the actual sources of the flow (technological representativeness).

2.2.2.4. Temporal Boundaries

As recommended in Sundqvist (1999), the temporal boundaries are defined according to processes rather than by any time element. Process-related temporal boundaries are used because, although rates of emission are very different for each option, the time integrated potential emissions over functionally equivalent time horizons may not be.

The studied function is the stabilization of the waste and since it can be characterized by the five stages of landfill gas production (initial, oxidation, acid anaerobic, methane and maturation), the gas yield (total m^3 produced) can be used as an indicator of the performance of the systems. Since this yield depends on design and operation parameters, it is different for the two options and hence, a unique volume cannot be used as a performance indicator for the options but a fraction of the maximum yield (95%) can. The rate of landfill gas generation is also dependant on design and operation parameters, so the time to reach the target value, i.e. the temporal boundary for the system, will be different.

A temporal boundary must also be specified during the environmental impact evaluation. This is the case for air emissions given that their impacts, due to their atmospheric halflives, are felt for different time periods. The effects of the greenhouse gases will be quantified over a period of 100 years, according to the recommendations of the environmental impact evaluation method that is used, the EDIP method (Environmental Design of Industrial Products) (Wenzel *et al.*, 1997). An infinite period is used to quantify ozone depletion, and photochemical smog formation will be quantified over a period of 4 years, again according to EDIP recommendations.

2.2.2.5. Physical Boundaries

The physical boundaries refer to the delimitation between processes that occur in the technosphere and the ones that occur in the ecosphere. This boundary is usually evident. In the case of landfills, it is specified as: 1 mm outside the liner and 1 mm over the final cover. All substances within these boundaries do not contribute to the elementary flow inventory.

2.2.2.6. System Description

The unit processes included in the six life cycle stages of the systems are shown in more detail for both options in Figure 2-4. They will be further developed during the inventory phase of the LCA.

a) <u>Site Development</u>

- The preoperational suitability studies include all activities conducted in order to identify an acceptable site (includes characterization), all suitability studies, public forums and hearings to achieve licensing.

- The buildings and structures built on the site are the access gate, the gatehouse and personnel support buildings, the equipment storage buildings and the truck platform scales.

- Utilities (electrical, sanitary and potable water) are needed for the operation of the site and this need can be met by connecting to the local utility grid or by providing an in-house solution (septic tank or well for example) depending on the availability.

- Roads must be built to access to the facilities and cell and the local public roads may have to be upgraded for heavy truck transport.

- The buffer zone around the cell, the site entrance and administrative buildings areas have to be landscaped. Low-level landscaping, expected to consist only of preparing and seeding bare soil with grass, is applied to the buffer zone, while more extensive landscaping may be applied to the buildings and site entrance.

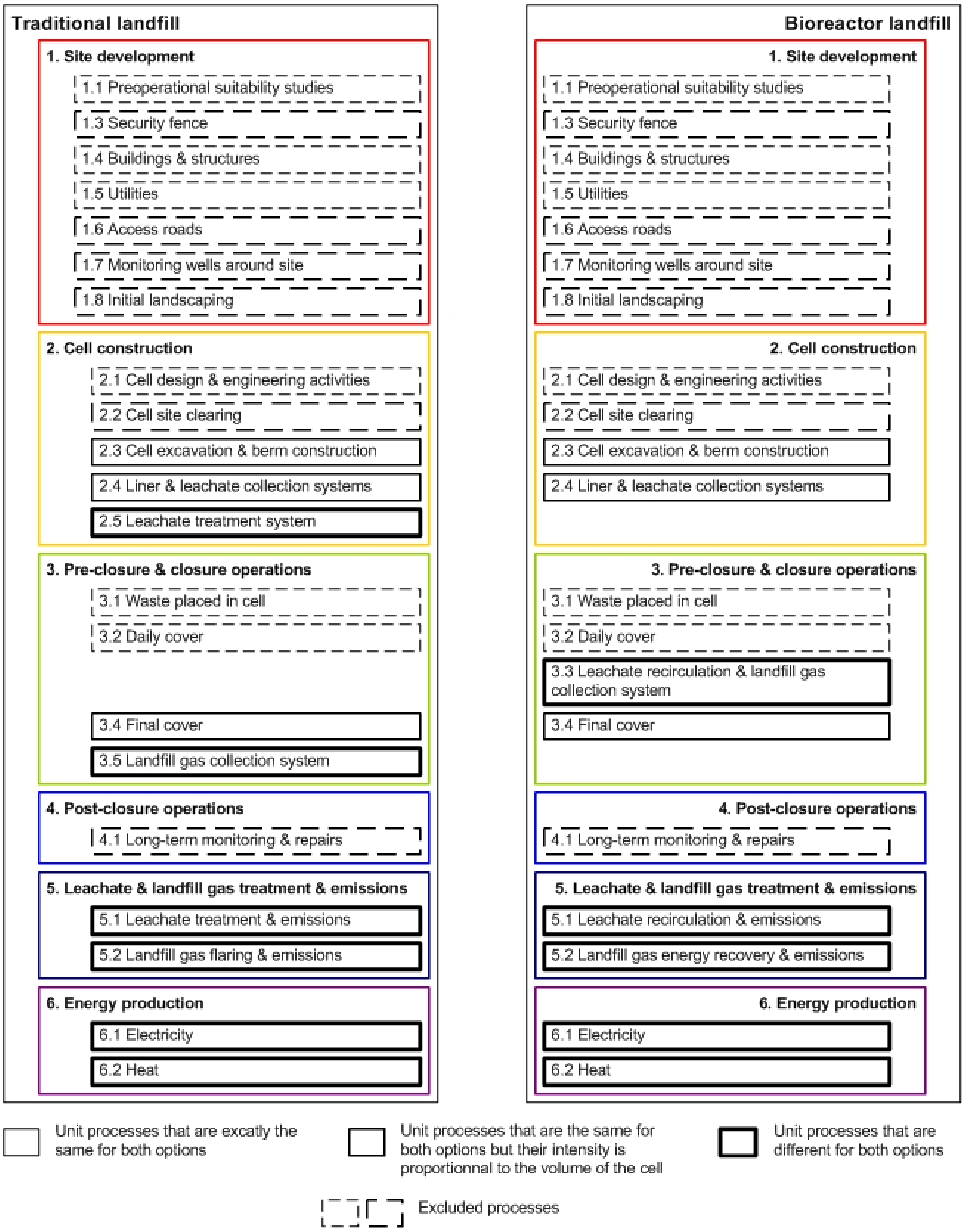

Figure 2-4: Life Cycle Stages Considered (Details).

b) Cell Construction

- The cell design and engineering activities cover the detailed engineering design of the facility, any hydrogeological studies and other studies or analyses.

- The liner system is identical for both options and is made up of five layers. These layers are, from the outer layer inwards: geosynthetic clay liner (GCL), geomembrane (flexible membrane liner or FML), geonet, another geomembrane and a protective geotextile. The leachate collection system is again identical for the two options. It is made of a layer of draining material (gravel) in which a network of collecting pipes is embedded.

- The leachate treatment system has to be put in place for the engineered landfill, it includes the storage and aeration ponds and the outlet pipe which leads to the receiving body of water.

c) Pre-Closure & Closure Operations

- Since the amount of waste and the rate at which it is disposed of is assumed to be the same for both options, all activities pertaining to waste placement and daily cell covering were treated as such.

- The leachate recirculation and landfill gas collection for the bioreactor cell is done through the same network of pipes embedded in horizontal trenches filled with gravel. The system is installed incrementally in the waste mass while the cell is filled with waste.

- Once both cells are filled with waste, they are closed and capped with the same final cover made up of four layers, which are (from the interior towards the exterior): sand, geomembrane, sand and organic soil.

- In the case of the engineered cell, after closure, vertical wells (partially perforated pipe in gravel with a bentonite seal) are drilled in the waste mass and used to collect the landfill gas produced by the waste degradation.

d) Post-Closure Operations

- Long-term monitoring and repairs involve routine environmental monitoring, maintenance of the leachate and landfill gas collection systems and repairs in the final cover due to settling and erosion.

e) Leachate & Landfill Gas Treatment & Emissions

- The leachate is generated by the infiltration of precipitation water in the landfilled waste (the daily cover is not impermeable) and it accumulates at the bottom of the cell in the leachate collection system, from which it is pumped and either treated in the case of the engineered cell (the treated leachate is released to a receiving body of water) or recirculated through the waste in the case of the bioreactor cell. For the latter, since the moisture content of the waste is the most important parameter influencing the rapid stabilization of the waste, it is possible that fresh water has to be injected in the waste to reach and maintain the target moisture level. The lining system is not a perfect barrier so a small amount of leachate is released to the environment. Leachate is still produced after closure: the capping system not being perfectly impermeable, precipitation water still enters the cell. The amount generated and collected gradually diminishes but its pumping and treatment must be maintained. In the case of the bioreactor, the leachate is recirculated and its volume controlled until the stabilization of the waste is attained.

- The fate of the collected landfill gas is different for both options. It is simply flared in the case of the engineered cell. For the bioreactor cell, the greater generation rate allows energy to be recovered from the collected gas. To do this, it is first dehydrated and then it can be either compressed and transported through pipelines to a specially adapted boiler to produce usable steam, i.e. heat, or directly burned on site in an internal combustion engine (ICE) to produce electricity. In both cases, the collection system and the final cover is not 100% efficient. Some gas is released to the environment though an appreciable quantity is transformed (for example methane is oxidized to carbon dioxide) by micro-organisms present in the organic soil cover.

f) <u>Energy Production</u>

- Since energy can be recovered from the collected landfill gas in the case of the bioreactor in the form of electricity or heat, both situations have to be considered. The other form has to be supplied to the system by other means (as mentioned before, a natural gas electrical power station and a natural gas industrial boiler). However, in the case of the engineered landfill, both forms have to be supplied to the system by external means since no energy is recovered from the collected landfill gas.

As can be seen, many life cycle stages are shared by both options. Some are assumed to be exactly the same, others only differ in their intensity, i.e. they include the same activities (material or equipment needs) but the amount used (kg of material or hours of work time) is different and proportional to the volume of the cell. Other life stages are totally different in terms of the materials or activities they include.

2.2.2.7. Excluded Processes

The unit processes that are assumed to be exactly the same for both options can be excluded from this comparative study since they will cancel themselves out in the comparison.

Due to time constraints and lack of information, some of the processes which differ in intensity for the two options have also been excluded as is indicated in Figure 2-4.

Secondary processes not exclusively dedicated to MSW management were also initially excluded. Excluded processes include the construction of infrastructure (except the landfill itself) and other capital goods or the human activities associated with the various unit processes. Maintenance of equipment and other capital goods is excluded as information on these processes is not generally available, and it is assumed that they make a relatively small contribution to the environmental impacts of the different systems.

2.2.2.8. Initial Inclusion Criteria for Inputs and Outputs

Three cut-off criteria can be used to determine the inclusion of the inputs and outputs identified: mass, energy and environmental significance. Physical inclusion criteria (mass and energy) are fixed at 1% of the total inventory, according to ISO 14 041 (ISO, date). Also, when an input or output presents a recognized environmental impact, the physical criteria are not applied; i.e., the toxic substance is kept in the inventory regardless of its amount. The application of these inclusion criteria permitted the progressive refinement of the system boundaries, allowing those unit processes whose contributions are insignificant to be eliminated from the systems. This is particularly useful when some elementary flows of a unit process cannot be quantified.

However, since the systems considered do not include a large number of unit processes, all relevant flows identified, either directly or included in data sets from commercial databases, have been included in the systems.

2.2.3. *Data Category Description*

The data used for the LCI can be classified according to source, type, level of aggregation, role they have in the inventory, associated uncertainty and the types of technology they describe.

2.2.3.1. Source-Based Data Classification

a) Primary, or Plant-Specific Data

The LCA practitioner can directly access this type of data or has a direct input into the collection process. This source is preferred when the LCA is conducted for a specific facility. For the present study, technology types are being compared and the performance of individual facilities is of limited interest. Primary data was used when 1) no other sources of data are available or 2) industry averages are being calculated.

b) Secondary Data

In this case, the data is not collected specifically for the LCA being conducted, and the practitioner has no input into the data collection process. Metadata is usually lacking, (e.g. data collection practices and variability). Secondary data is expected to play an important role in the present LCA.

2.2.3.2. Type-Based Data Classification

a) <u>Measured Data</u>

Measured data are monitored or sampled. This type of data was favoured in this study whenever available from a representative group of facilities (to account for variability). This type of data can also be used alongside modeled data when determining the spread of a specific parameter or for validating the latter.

b) <u>Modeled Data</u>

This type of data results from the use of models to represent processes or phenomena. Model validity greatly affects the quality of the deduced data. Since the influence of different design and operational parameters can best be accounted for using models, this type of data was favoured. Measured data may supplement and/or validate modeled data.

c) <u>Non-Measured Data</u>

This classification includes data based on professional judgment and educated guesses. This type of data was used only when no other data was available.

2.2.3.3. Data Classification Based on Aggregation Level

The aggregation level of data refers to the number of unit processes that are represented by the data. Completely disaggregated data describe each individual unit process making up a specific life cycle stage or system. Highly aggregated data can, for example, represent cradle to gate data about a specific material, up to its entering the product. High levels of aggregation for ancillary materials were prioritized for this study, as this approach greatly simplifies data collection, whereas for data pertaining to actual landfilling processes, highest levels of disaggregation were prioritized.

2.2.3.4. Role-Based Data Classification

The mass flows inventoried were classified according to their role in the product systems. They can either be:

- Inputs, such as raw materials, intermediate products and energy carriers;
- Outputs, such as final products, intermediate products, co-products, waste and emissions to air, water and soil.

All of these were included in the study, although only elementary flows (inputs taken from and outputs emitted to the environment) were, by definition, included in the life cycle impact assessment.

2.2.3.5. Uncertainty-Based Data Classification

LCI data can also be deterministic or probabilistic. Deterministic data are point estimates of specific parameters, which imply great confidence in the reported value. Probabilistic data account for uncertainty and variability in the parameter value, and can be expressed by ranges or probability distribution functions (triangular, normal, log-normal, etc.).

2.2.3.6. Technology-Based Data Classification

a) Average Data

This type of data is used for information-oriented LCA, whose goal is allocating present environmental impacts to the studied product system. In this type of study, the *ceretis paribus* principle applies, meaning all processes outside the direct control of the mandating party remain unchanged. The data used must therefore represent average technologies mobilized by the product system (e.g. average industrial mixes). Since the present LCA evaluates the impact of a decision, this type of data may not be pertinent and was therefore avoided for certain life cycle stages.

b) Marginal Data

This type of data is used for decision-oriented LCA, which aim at evaluating the impact of a particular (small) change in production. The *ceretis paribus* principle no longer applies, and the data used must represent the actual technologies affected by the decision (e.g. a change in energy use may affect energy output of thermal power stations and leave unaffected hydroelectric plants).

c) Discrete or Scenario-Based Data

This type of data is used for decision-oriented LCA where the scope of the change analyzed is very large. For example, capital investments may need to be modeled to account for changes brought on by the decision.

In this study, the impact of a decision (engineered vs. bioreactor landfill) was analyzed, and both marginal (for e.g. energy production) and discrete data were used when pertinent. When no major difference between average, marginal and discrete data was expected, average data, which is more readily available, was used.

2.2.4. *Data Quality Requirements*

The reliability of the study's results and conclusions depend on the quality of the data that is used, so it is important to assure that this data follows requirements specified in accordance with the goal of the LCA. As mentioned in the research proposals (Samson *et al.*, 2002a & 2002b), the study was conducted with the data that could be obtained within the limited time available. This has important consequences on the accuracy and precision of the data used, since it was impossible to obtain measured data from all production sites within the time frame of the study, and generic commercial databases had to be consulted. However, the quality of the data used was sufficient to attain the goal of the study. It would, nevertheless, be useful to allocate more time to gather data of higher quality (precision, accuracy and representativeness), in order to further develop the studied options and raise the confidence level of the conclusions of this study.

For the present study, data quality requirements were set as follows:

- The data used had to ideally not be older than five years unless it could be assumed that the unit process(es) it characterized had not changed since the data was obtained.
- The geographical zone from which data was gathered was North America. The US EPA LCI data on waste management and the Franklin database, being specific to that zone, were preferred. However, due to the limited amount of data contained in these two sources, European databases were also used, thus creating a regional bias. The Canadian Database on Raw Materials, from the federal Ministry of Natural Resources, would raise the confidence of the results on the geographical standpoint; however the highly aggregated data it contains could not be used to conduct impact assessment since the emission categories used do not include characterization factors.
- Data on technological performances of unit processes had to be representative of reality.
- The completeness and precision of the data were not evaluated in this study.

⇒ Recommendations for public disclosure of the LCA's results:

For LCAs used to support a comparative assertion that will be disclosed to the public, the above-mentioned data quality requirements shall be addressed, as well as the following (ISO 14 042, 1998):

- The completeness of the data: the measure of the divergence between the number of elementary flows identified and the actual number of such flows in a unit process (as described in literature sources for example);
- The precision of the data: the measure of the variability of the data values for each data category expressed (e.g. variance).

The present study should therefore be revised according to these standards prior to public disclosure.

2.2.5. *Allocation Rules*

When a recycling or energetic valorization system intervenes in the life cycle of a product or service, it may be necessary to apply allocation rules so as to determine what proportion of the inventory is to be given to which system, either the producer or the user of the recycled product (ISO 14 041, 1998). These rules must reflect as close as possible the fundamental relations and characteristics of the system's inputs and outputs. The recycling can be done in closed or opened loop configurations. In the case of a closed loop system, no allocation is done. In an opened loop system, the allocation rules prescribed by ISO standard 14 041 must be followed. The allocations rules, in order of priority, are:

- Allocation should be avoided when possible. To do so, it is possible to: 1) divide the unit process to allocate in two or more sub-processes; or 2) expand the system's boundaries to include the additional functions associated with the co-products.
- If allocation cannot be avoided, it is convenient to divide the inputs and outputs amongst the different co-products according to the physical relationships that exist between them, i.e. mass.
- When a physical relationship cannot be identified, it is convenient to use another type of relationship, i.e. the economic values of the co-products, to divide the different flows.

Allocation problems could have appeared in the present study, when energy is recovered from the landfill gas, but allocation was avoided by the expansion of system boundaries.

2.2.6. *General Assumptions*

- The daily cover represents 10% of the waste volume.

- To calculate the size of the cell (m^3), the density of the waste was considered to be 800 kg/m^3 for the engineered cell and 1000 kg/m^3 for the bioreactor cell. This means that the same mass of waste will takes 25% less space in the bioreactor cell than in the engineered cell.

- The effective landfill gas yield is only a fraction of the maximum yield (Biochemical Methane Potential) obtainable from the waste composition considered (it is the same for both cells); it is controlled by cell design and operation parameters. Since this fraction was not precisely known, a range of values was used to evaluate its influence on the assessment results; it is however assumed that this fraction was higher for the bioreactor than for the engineered landfill. The ranges selected for effective yield fraction was from 40 to 70% (in 10% increments for a total of 4 values) for the engineered landfill and from 60 to 90% for the bioreactor landfill.

- The post-closure monitoring period, during which both leachate and landfill gas are collected, is of 30 years for both options. After this period, all activities on the site stop. For the bioreactor landfill, however, the post-monitoring period is not included in its totality in the study since the temporal frontier, i.e. the end of the study period, is set by a greater landfill gas generation rate.

- The compositions of the landfill gas were considered to be the same for both options.

- The CO_2 produced from the waste, either directly from degradation or from the treatment of the landfill gas (combustion in the flare, ICE or boiler) or partial oxidation in the soil cover or the treatment of the leachate (oxidation in the aeration pond) is biogenic and as such was not considered in the greenhouse gases inventory (GWP).

- As was mentioned above, not all of the potential landfill gas is produced since the conditions in the waste mass are not ideal. The carbon contained in this un-emitted fraction is in a way stored in the landfill waste and thus the CO_2 that would have been produced from this carbon, is removed from the atmosphere and the carbon cycle and as such, represents an environmental credit. This CO_2 sink is then calculated from the maximum potential yield landfill gas of the waste and the effective yield produced in the time period considered in the study (production of 95% of the total yield).

2.2.7. *Environmental Impact Evaluation*

2.2.7.1. Environmental Impact Evaluation Method

Since no environmental impact evaluation method has yet been developed specifically for the North American region, i.e. taking into account its geographical and ecological context, it is necessary to use one of the available methods developed by European LCA practitioners. However, since this is a comparative study, all that is needed is a reference point to which all the options will be compared. The bias which the use of the European context generates in the results will be the same for each option, so it can be disregarded.

The potential environmental impact evaluation method EDIP (Environmental Design of Industrial Products) (Wenzel *et al.*, 1997) was selected for this study. EDIP is well documented and follows a problem-oriented approach. It was developed in Denmark by a multidisciplinary team with representatives from five Danish industries, the Technical University of Denmark, the Confederation of Danish Industries and the Danish Environmental Protection Agency.

The EDIP method follows the recommendations of the ISO 14 042 standard for the evaluation of the environmental impacts during an LCA. The present study was limited to the compulsory elements of the standard, i.e. the classification and characterization. This has also limited the geographical bias introduced in the results by the European origin of the method, as the characterization factors used are based on specific physical properties of the substances emitted in the environment and so are independent of the location of the emissions. Since the European context is clearly apparent in the normalization and weighting steps that follow and that are included in the method, these elements were not used.

2.2.7.2. Impact Categories Considered

The impact categories considered by the EDIP method are grouped in three classes: environmental impacts, natural resources consumption and impacts on the work environment. The consumption of natural resources was individually calculated, while impacts on the work environment were not evaluated in the present study, as they do not contribute to achieving the goal of the study. The method does not consider the following impacts: noise, odours and land use.

The environmental impact categories included in the method are presented in Table 2-1.

Table 2-1: Environmental Impact Categories Considered by the EDIP Method (Wenzel et al., 1997)

Environmental Impact Category	Indicator Result	Impact Scale
Global warming potential (GWP)	g CO_2 equivalents	global
Ozone depletion potential (ODP)	g CFC11 equivalents	global
Photochemical ozone creation potential (POCP)	g C_2H_4 equivalents	regional
Acidification potential (AP)	g SO_2 equivalents	regional
Eutrophication potential (EP)	g NO_3 equivalents	regional
Ecotoxicological Impacts – Ecotoxicity – Water, Acute (ETWA) – Ecotoxicity – Water, Chronic (ETWC) – Ecotoxicity – Soil, Chronic (ETSC)	 m^3 water /g m^3 water /g m^3 soil /g	local, regional
Toxicological impacts (human) – Human Toxicity – Water (HTW) – Human Toxicity – Air (HTA) – Human Toxicity – Soil (HTS)	 m^3 water /g m^3 air /g m^3 soil /g	local

The global warming potential affects the environment on a global scale. The potential contribution of every greenhouse gas is represented by an equivalence factor (in g CO_2 equivalents) obtained from the emissions scenarios in the 1994 status report from the Intergovernmental Panel on Climate Change (IPCC). The effects of the inventoried emissions are quantified over a 100-year period.

The ozone depletion potential is also a global-scale impact. Its equivalence factors, g of CFC 11 equivalents for the various substances affecting the stratospheric ozone layer, are taken from the 1992/1995 status reports of the Global Ozone Research Project, a joint United Nations Environment Programme (UNEP) and World Meteorological Organization (WMO). An infinite time period is used to quantify the effects of the inventoried emissions.

The photochemical ozone creation potential is a regional-scale impact. Its effects are felt within a radius of 1 000 km (Wenzel *et al.*, 1997). The equivalence factors (g C_2H_4 equivalents) for each substance considered are taken from the 1990/1992 reports of the United Nations Economic Council for Europe (UNECE). Their values depend on the background concentration of NO_x.

Acidification and eutrophication potentials are also regional-scale impacts. The acidification equivalence factors (g SO_2 equivalents) are based on the number of protons (H^+) that can be theoretically released by the substances considered. The eutrophication equivalence factors (g NO_3 equivalents) are based on the number of nitrogen and phosphorus atoms present in the substances considered released in the air, water and soil.

Ecotoxicity, i.e. the toxicity effects on organisms in the environment due to the release in the air, water and soil of anthropogenic substances, is a local scale impact and its potential is based on a chemical hazard screening method, which looks at toxicity, persistency and bioconcentration. Fate (distribution of substances in various environmental compartments) is also taken into account. Ecotoxicity potentials are calculated for acute and chronic ecotoxicity for water and chronic ecotoxicity for soil. Since fate is included, an emission to water can lead not only to chronic and acute ecotoxicity for water, but also for soil. Similarly, an emission to air can lead to ecotoxicity for water and soil.

Human toxicity is an impact generally felt on a local scale, and its potential is also based on a chemical hazard screening method, which looks at toxicity, persistency, bioconcentration and bioaccumulation in food and living tissues. The fate of substances in various environmental compartments is also taken into account. Human toxicity potentials are calculated for exposure via air, soil and surface water.

Ecotoxicity and human toxicity are determined by laboratory tests on living organisms or by observations on humans. Persistence in the environment is determined by a biodegradability test. Bioconcentration potential is based on the octanol-water partition coefficient.

2.2.7.3. Calculation Method

The software program that was used for the calculation of the inventory and the evaluation of the potential environmental impacts associated with the emissions identified in the inventory is the SimaPro 5 software, developed by Pré Consultants (Netherlands).

2.2.8. *Equivalence of the Compared Systems*

For comparative studies, the equivalence of the systems must be evaluated before the results can be interpreted (ISO 14 040, 1997). The following methodological considerations were therefore examined: the performance of the systems and boundaries, the quality of the data used, the allocation rules, the inventory flows and environmental impact evaluation methods. In accordance with international standard requirements, any differences in any of the parameters mentioned were reported.

⇒ Recommendations for public disclosure of the LCA's results:

In the case of comparative assertions disclosed to the public, the systems' equivalence evaluation shall be conducted in accordance with the critical review process described in the ISO standards (ISO 14 040, 1997).

2.2.9. *Interpretation Methods*

The result of the characterization is an evaluation of the environmental load for each of the impact categories considered. The comparison of the different management options was done one impact category at a time. The following analyses were performed:

- A contribution analysis, to determine the contribution of each life cycle stage, unit process and substance inventoried on the total impact for each option;
- A sensitivity analysis, to asses the sensitivity of the results on the effective landfill gas yield;
- The comparison between options was done on a category by category basis.

2.2.10. *Critical Review*

A critical review is a process used to verify if an LCA satisfies the international standard requirements. It is a facultative process (ISO 14 040, 1997). The present study was not subjected to a critical review.

⇒ <u>Recommendations for public disclosure of the LCA's results:</u>

The use of LCA results to support comparative assertions raises special concerns and requires critical review, since this application is likely to affect interested parties that are external to the LCA study. Critical reviews shall be conducted in accordance with the critical review process described in the ISO standards (ISO 14 040, 1997).

2.2.11. *Limits of the Study*

This study was conducted strictly for comparative reasons. No interpretation of a specific environmental impact should be made, nor any conclusion be drawn beyond this very specific context.

The number of design and operational parameters under investigation were limited to allow the research project to remain feasible with the allocated resources. Specifically, upstream processes (sorting, pre-treatment), which change MSW composition and state, and downstream processes (landfill fate after stabilization), were ignored. Further investigation may reveal these parameters to greatly influence the relative environmental performance of the assessed technologies.

Since there is a lack of specific inventory data for North America and of time in which to do the study, a significant amount of data from European databases was used. This will definitely affect the study's results. However, it is also important to mention that the data quality requirements for a comparative LCA intended for internal use only are not as stringent as for an LCA released to the public.

One major impact of MSW management is land use. The bioreactor landfill may prove to be more efficient in this aspect since waste volumes are more rapidly reduced, allowing the re-use of the freed up volume for the acceptance of further waste. The land use impact category was excluded from the present study due to the lack of simple and appropriate models and because the impact is assumed relatively similar for both technologies when post-stabilization landfill management is ignored.

An uncertainty analysis, which would give an indication of the robustness of the conclusions, could not be carried out with the allocated resources. Without knowledge of the degree of confidence one may have in the results, conclusions and recommendations drawn from the deterministic results may be unwarranted.

Finally, the use of LCA results to support comparative assertions requires special attention since this application is likely to affect interested parties that are external to the LCA study. In order to decrease the probability of misunderstandings or negative effects on external interested parties, the present study shall be revised according to the ISO standards prior to public disclosure.

2.2.12. *Final Report Format*

LCA results must be communicated in a precise, clear and transparent way (ISO 14 040, 1997). Each phase of the LCA (goal and scope of the study, inventory analysis, potential environmental impacts evaluation, and interpretation of results) is presented in a separate chapter in the present final report. Any new development in the methodology was documented, as were the interpretations and subjective choices made during the course of the study.

3. LCA PHASE II: INVENTORY ANALYSIS

This section presents the second phase of the LCA study: the inventory analysis. It describes the data collection methodology, the inventory analysis for each option as well as the inventory analysis limitations.

3.1. Data Collection Methodology

As previously mentioned, inventory analysis and impact evaluation calculations for this study were conducted using the SimaPro 5 software, which includes several databases. Some of the software's data has been modified for the purpose of the present study. New data has also been added to the software's database.

Data quality requirements are as defined in the scope of the study (Section 2). During the data collection, the first criterion to be considered was the data source (time, geography and technology criteria).

The following sections describe the product systems for both landfill options and present data sources and categories, assumptions and calculation procedures as well as the inventory results.

3.2. Description of the Product Systems

The process flow diagrams included in Appendix B illustrate the product systems for both options. The following paragraphs describe the unit processes included in these diagrams. Many processes are the same for both options so they are presented here only once, when processes only concern one option it is stated as such in the text. The system includes the production and transport to the landfill site of all materials used.

3.2.1. *Cell Excavation and Berm Construction*

The cell in which the waste will be placed is first excavated. Part of this material is used to build a berm, around the excavation using the excavated material. The construction of the berm is included in the excavation unit process.

3.2.2. *Liner and Leachate Collection Systems*

A double liner system is then placed at the bottom of the excavation. The primary liner consists in a high density polyethylene (HDPE) geomembrane with a protective polypropylene (PP) geotextile placed over it. The secondary liner is placed under the primary one as an additional security measure and consists in another HDPE geomembrane with a geosynthetic clay liner (GCL, two PP geotextiles with bentonite in-between) underneath. A drainage medium or geonet (an HDPE mesh) is placed between the two liners so as to enable the detection and collection of any leachate that would leak through the primary liner.

The primary leachate collection system consists in HDPE perforated pipes running the whole width of the cell's floor and placed about 50 m apart center-to-center on the liner system. A gravel layer is placed over this network of pipes to act as a protective and drainage medium. Each drainage pipe ends the collection pipe that runs the entire length of the cell floor and up its side and to the pumping station. The collection pipe is placed in a trench filled with gravel and the double liner system used on the cell floor extends around this trench. As an added precaution, there is an extra 2 m wide band of geonet in the liner system, underneath the drainage and collection pipes. The floor is sloped between the drainage pipes and along their length to facilitate the leachate collection. The collection pipe is also sloped so that there is a lowest point on the cell floor; a pipe is run to the geonet layer at this point to collect the leachate that may have leaked through the primary liner and act as a secondary leachate collection system. The pumps used to collect the leachate from the two collection systems were not included in the study.

3.2.3. *Leachate Treatment System (Engineered landfill)*

For the engineered landfill, the collected leachate must be treated before being pumped to a receiving body of water, i.e. released to the environment. The treatment consists in a stay in an aeration pond during which a large fraction of the compounds found in the leachate is either oxidized (Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), NH_3), precipitated (metal, phosphorus) or volatilized (trace organics like benzene). A large volume of sludge is produced and has to be periodically removed from the aeration pond; however this activity was not included in the system. A storage pond has to be used since there is no treatment during the winter period (15^{th} of December to the 15^{th} of May). The aeration pond is divided by curtains in four compartments equipped with aerators through which the leachate flows sequentially, the retention time in the aeration pond, or treatment time, is of 50 days. The energy used by the aerators is included in the system but not the energy used by pumps to move the leachate through the system. Both ponds are built in the same way, they are excavated, a berm is built around the excavation and a liner system is placed at the bottom of the excavation (GCL and HDPE geomembrane).

3.2.4. *Leachate Recirculation and Landfill Gas Collection System (Bioreactor Landfill)*

In the case of the bioreactor landfill, the leachate recirculation system is also used to collect the landfill gas produced by the anaerobic degradation of the waste. It consists of a network of horizontal trenches built across the cell as it is filled with waste. They are excavated in the waste and filled with gravel with a HDPE perforated pipe placed at the center. The pipes are connected by a valve system to separate leachate injection and landfill gas collection pipes, each connected to main feeder and collection pipes that run the length of the cell. The energy used by the pumps to recirculate the leachate and the compressors to collect the landfill gas was not included in the system.

3.2.5. *Final Cover*

The final cover placed on the waste is used to prevent precipitation water to penetrate into the waste and generate leachate and to keep the landfill gas produced by the waste inside the cell so it can be collected and treated. It consists of a layer of a HDPE geomembrane between two layers of compacted sand, the lower layer protects the flexible liner from any sharp object in the waste underneath and the top layer is used as drainage medium for the precipitation water so it does not accumulate in depressions in the cover and infiltrate the liner through small tears in the fabric. A layer of compacted organic soil is finally placed on top of the sand and seeded. The seeding and landscaping of the final cover have not been included in the study.

3.2.6. *Landfill Gas Collection System (Engineered landfill)*

In the case of the engineered landfill, the landfill gas collection system consists in vertical wells drilled in the waste mass after the final cover is put in place. However, it is assumed that the waste is placed in the cell in sections covering the whole height of the cell, thus a section, once it has attained its projected height, receives its final cover and wells can be drilled in. This enables the collection of the landfill gas before the end of the active period and closure of the cell. The wells have an HDPE perforated pipe placed at their center and are filled with gravel with a bentonite plug at the top, to seal the well and prevent leaks of landfill gas to the atmosphere. The energy used by the compressors to collect the landfill gas is not included in the system. The landfill gas is dehydrated before being used on-site by the ICE and off-site by the modified boiler, after having been compressed and transported by pipelines. All these processes have also been excluded from the study.

3.2.7. *Leachate Treatment and Emissions*

The leachate arises from the infiltration of water in the waste as it flows down through the waste mass and becomes contaminated with waste components (dissolved and suspended) and products of their reaction (mainly hydrolysis) along with waste degradation by micro-organisms. The water comes from the precipitations on the cell, so there are losses due to run-off and evapo-transpiration; it also has to penetrate through the final cover if it is installed, the amount of water that enters the system diminishes during the active phase of the landfill since more and more sections of the cell are covered. As the cover is not 100% efficient and some water still enters the waste, this volume may increase with time and the appearance of small tears in the geomembrane. Once the leachate reaches the bottom of the cell, it is stopped by the liner system and accumulates until it is pumped out of the cell by the leachate collection system to be treated (engineered cell) or recirculated in the waste (bioreactor cell). However, the liner and collection systems are not 100% efficient and some leachate may eventually leak out of the cell and into the natural soil underneath.

In the case of the bioreactor, since the waste moisture content is controlled and maintained at the field capacity of the waste, it might be necessary to add water to the waste during the operation of the cell. This addition is done through the system of horizontal trenches. The water used to supplement, if needed, the waste in moisture was assumed to be taken untreated from either surface or underground sources near the site, no transport was considered and the pumping of this water was also excluded from the study. This added water was however taken into account in the leachate volume calculation.

3.2.8. *Landfill Gas Treatment and Emissions*

The landfill gas production is represented by a model developed by the Solid Waste Association of North America (SWANA), using different values for the model parameters to reflect the different conditions in both types of cells studied. One of the parameters used is the yield (in m^3/tonne of waste) that can be obtained from the waste. As was mentioned before, this value was assumed to vary between 40 and 70% of the maximum yield calculated from the composition of the waste in the case of the engineered cell, and between 60 and 90% of this same maximum in the case of the bioreactor cell. A fraction of the landfill gas generated is collected and then treated. How much is collected changes with time as the installation of the final cover and the collection system progresses. The treatment methods (flare for the engineered cell and ICE and boiler for the bioreactor cell) have different destruction efficiencies and emission factors. The final cover and collection system are not 100% efficient and some landfill gas escapes to the atmosphere. However, while the gas passes through the soil cover, micro-organisms present in the organic soil oxidize some of the components present in the gas and transform them into CO_2.

3.2.9. *Energy Production*

The amount of energy produced by the systems represents the maximum of energy that can be recovered from the landfill gas produced and collected by the bioreactor, whether as electricity or heat. The engineered cell system has to be supplemented with production processes (natural gas electrical power station and industrial boiler) no matter how much landfill gas it produces. The bioreactor, since it can only produce one form of energy at a time and because its gas production varies so the energy output is not always equal to the maximum calculated, also has to be supplemented with production processes, to bring the considered energy form (electricity for example) production to the maximum output and to add the production of other energy form (heat in this example).

3.3. Data Sources and Categories

Many data categories were used during data collection (see section 2.2.3). The following table summarizes inventory data sources and categories for the different group of unit processes considered. More detail regarding data sources and characteristics are presented in the following paragraphs while process cards are included in Appendix E.

Table 3-1: Data Sources and Categories

Unit Process	Data Source	Data Category
Materials and energy production	SimaPro 5 software databases	Generic data
Non road equipment	U.S. EPA's NONROAD model and Franklin Associates database	Generic data
Transportation (by truck)	Joint EMEP/CORINAIR Emission Inventory Guidebook 3rd ed. and Franklin Associates database	Generic data

3.3.1. *Materials*

The material production was modeled using generic data found in the many databases provided with the SimaPro 5 software. Preference was given to the database produced by Franklin Associates Ltd since it is the only one from North America. To simplify the system and reduce the number of unit processes considered, the production or processing data obtained from the European databases were modified: when energy production processes or transport processes were referred to, they were replaced by their equivalent from the Franklin Associates database. These processes can be seen as auxiliary to the particular unit process considered, i.e. the European plant where the process takes place has been changed to a U.S.-based one which is supplied with North American energy and which uses North American trucks, the rest remains the same.

3.3.2. *Non-Road Equipment*

The equipment considered was modeled using data found in the NONROAD model published in 2000 by the U.S EPA's Office of Transportation and Air Quality (Internet). Certain information pertaining to the equipment was required: type of equipment, power and work period. The results of the calculations included the fuel consumption (all the equipments were considered to be running on diesel) and the atmospheric emissions for several pollutants: CO_2, CO, total hydrocarbons (which can be converted with supplied factors into total organic gas, non-methane organic gas, non-methane hydrocarbons and volatile organic compounds), NO_X, SO_2 and particulates.

3.3.3. *Transportation*

The transportation by truck (diesel consumption and air emissions) was modeled using data found in the Joint EMEP/CORINAIR Emission Inventory Guidebook published in 2001 by the European Environment Agency (Internet) for Diesel Heavy Duty Vehicles (16 – 32 t payload). Certain information pertaining to the transport modeling was required: distance, number of trips and loading factor. The results of the calculations included the fuel consumption (all the trucks were considered to be running on diesel) and the atmospheric emissions for several pollutants: CO_2, CO, volatile organic compounds (VOCs), methane, non-methane volatile organic compounds, NO_X (sum of

NO and NO_2), N_2O, NH_3, SO_2, particulates and heavy metals (Cd, Cr, Cu, Ni, Pb, Se, Zn). The diesel pre-combustion resource requirements and emissions were quantified using data from the Franklin Associates database provided with the software.

3.4. Assumptions and Calculation Procedures

According to the functional unit of the study, the reference flows for both options were: one engineered landfill and one bioreactor landfill, both having a capacity of 600 000 tonnes. For each unit process, the material and energy requirements corresponding to these reference flows were determined and the calculations necessary to build this inventory are presented in Appendix D. These calculations necessitated a number of assumptions, which are presented in following paragraphs while unit process characteristics are summarized in Appendix C.

3.4.1. *Design Calculations*

The cell has the same rectangular shape for both options with a length-to-width ratio of 2 with the sides having a slope (above and under grade) of 30%. The slopes of the cell's bottom (2%) and top (5%) were ignored in the cell's volume and dimension calculations for reasons of simplicity.

The depth of the cell is less than its height. For the amount of waste considered in this study, a depth of 4 m was considered when in actuality, the excavated depth is only of about 2 m since there is a 2 m berm around the cell (trapezoidal section with a 3 m wide top and 30 % sloped sides). The height of the cell is dictated by the requirement that the landfill be integrated with its surroundings and by geotechnical constraints. The two cells under study were assumed to be constructed in the same site so they were assumed to have the same height. A height above the top of the berm of 16 m was chosen, giving a total waste depth of 20 m.

The cell volume and dimensions (length and width) were calculated taking into consideration the volume of the vertical wells (engineered cell) and of the horizontal trenches (bioreactor cell) that would be installed in the waste mass.

The vertical wells are usually installed in staggered rows on the top of the cell, 50 m apart center-to-center. However, the calculated dimensions of the cell resulted in a top too narrow to have staggered rows so the design was changed to two parallel rows, 13 m from the edges of the cell top (the wells are 44 m apart on the same row and 44 m from the well on the other row). The wells are drilled to a depth of 18 m (2 m from the bottom of the cell) and are 750 cm wide. The bentonite plug at the top of the well is 2 m thick. Each well has a collection pipe running to the same side of the cell, down its side and to the main collection pipe that runs the entire length of the cell at ground level.

The horizontal trenches are built in lifts at different heights in the cell; the highest lift being 2 m from the top of the cell, the lowest one being 6 m above the floor of the cell, the ones in between are 6 m center-to-center. The closest trenches to the side of the cell are 15 m from it. The trenches in the highest lift are about 15 m apart, the one in the other lifts are 20 m apart. The length of the trenches changes with their height because of the cell's slopped sides. They also start and end 20 m away from the side of the cell but for the pipe that reaches the side on one end, so it can be connected to the leachate feeder pipe and the landfill gas collection pipe. The section of the pipe that is not in the gravel trench is not perforated. The feeder and collection pipes go down the side of the cell straight to the main feeder and collection pipes that run the entire length of the cell at ground level.

The distance between the cells and the various pumping and treatment areas for the leachate and landfill gas are not know and hence, were not considered in the calculation of the main collection and feeder pipes.

The leachate treatment system's storage and aeration ponds have a capacity of 10 000 and 3 000 m^3 respectively. There have a depth of 4 m, including a 1 m berm around the excavation (trapezoidal section with 3 m wide top and 30 % sloped sides), so the actual excavation depth is about 3 m. The maximum height of water is 3 m.

3.4.2. *Materials*

The various material specifications considered in the calculations are given in the following table.

Table 3-2: Material Specifications Considered

Material	Specification	Density (kg/m^3)
Gravel, dry	Bank Loose	2 148 1 833
Sand, dry	Compacted Loose	1 824 1 543
Organic soil, dry	Compacted Loose	1 879 1 314
Bentonite, dry	Bank Loose	1 5721 246
Geosynthetic clay liner (GCL)	6 mm thick, 2 PP geotexiles (100 g/m^2) with bentonite (3500 g/m^2) in-between	--
HDPE geomembrane in liner	1.5 mm thick	955
HDPE geomembrane in final cover	1 mm thick	955
HDPE geonet	6 mm thick	940
PP geotextile	3.5 mm thick, 450 g/m^2	--
HDPE drainage pipe (leachate collection system)	150 mm diameter, DR11	7.40 kg/m
HDPE collection pipe (leachate collection system)	200 mm diameter, DR11	12.53 kg/m

Material	Specification	Density (kg/m^3)
PVC pipe (leachate treatment system)	100 mm diameter	1.62 kg/m
Steel in storage tank (leachate recirculation system)	1/10 to 1/4 in. thick	7800
Glass in storage tank (leachate recirculation system)	7 to 11 mils thick	2500
Aluminium dome for storage tank (leachate recirculation system)	1905 kg	--
Concrete for storage tank (leachate recirculation system) (steel reinforcement included)	Steel reinforcement for the concrete base represents 10% of the mass of the structure.	2 403
HDPE injection/collection pipes (leachate recirculation/landfill gas collection system)	150 mm diameter, DR11	7.40 kg/m
HDPE feeder pipes (leachate recirculation system)	75 mm diameter, DR17	1.38 kg/m
HDPE main feeder pipe (leachate recirculation system)	150 mm diameter, DR11	7.40 kg/m
HDPE collection pipes (landfill gas collection system, engineered landfill)	250 mm diameter, DR17	13.07 kg/m
HDPE main collection pipe (landfill gas collection system, engineered landfill)	From 250 to 400 mm diameter, DR17	From 13.07 to 28.96 kg/m
HDPE collection pipes (landfill gas collection system, bioreactor landfill)	150 mm diameter, DR17	4.97 kg/m
HDPE main collection pipes (landfill gas collection system, bioreactor landfill)	From 250 to 450 mm diameter, DR17	From 13.07 to 36.67 kg/m

3.4.3. *Non-Road Equipment*

All the excavation performed for the cells and the leachate treatment system's ponds are done using a hydraulic excavator-dump truck combination.

3.4.4. *Transportation*

The trucks used for the various transportations in the system are 10 m^3 4-axle trucks for the transport of bulk material (excavated material, gravel, sand and soil), 10 m^3 mixer trucks for the ready-mixed concrete transport and 40 t 5-axle trailer trucks (25 t payload) for the storage cell material transport.

The material excavated during the construction of the cell and leachate treatment system ponds was assumed to be transported 500 m to a temporary storage area. The fate of this material was not included in the study, it could be used as daily cover during the filling of the cells but this phase was excluded from the system as previously mentioned.

The bulk material used in the vertical wells, horizontal trenches and final cover are taken from a borrow pit situated 50 km from the site.

All the other materials used in the systems were assumed to be transported 100 km to the site.

3.4.5. *Leachate*

The amount of precipitation was set a 1 m/m^2/year.

The amount of leachate produced, collected, treated and released to the environment (fugitive leachate) was calculated taking into account the evapo-transpiration and run-off losses and the cover and liner efficiencies, which are given in the following table. They are the same for both systems except for the fact that the end of the study period is reached in the case of the bioreactor before the cover and liner efficiencies start to decrease.

Table 3-3: Leachate Production Parameters

Parameter	Value (%)
Evapo-transpiration losses	60
Run-off losses	From 0 to 1 year : 5 From 1 to 2 years : 10 After 2 years : 20
Cover efficiency	From 0 to 1 year : 0 From 1 to 2 years : 50 From 2 to 32 years : 99 After 32 years : - 0.01 (per year)
Liner efficiency	From 0 to 32 years : 99.99 After 32 years : - 0.01 (per year)

The composition of the leachate considered in the study for both systems are given in the following tables (according to Sich and Barlaz, 2000).

Table 3-4: Leachate Composition for the Engineered landfill (Sich and Barlaz, 2000)

Leachate Component	Concentration (mg/L)
BOD	From 0 to 1.5 years : 7 000 From 1.5 to 10 years : linear decrease from 7 000 to 1 000 From 10 to 50 years : linear decrease from 1 000 to 0 After 50 years : 0
COD	From 0 to 1.5 years : BOD/COD ratio = 0.8 From 1.5 to 10 years : BOD/COD ratio in linear decrease from 0.8 to 0.3 From 10 to 50 years : linear decrease to 100 mg/L After 100 years : 100 mg/L
Total suspended solids	57E+0
NH_3	343E+0
PO_4	8.5E+0
Benzene	2.5E-3
Toluene	87E-3
Xylenes	45.1E-3
Ethylbenzene	9E-3
Chloroform	2.5E-3
Carbon tetrachloride	2.5E-3
Ethylene dichloride	2.5E-3
Methylene chloride	4E-3
Trichloroethene	2.5E-3
Perchloroethene	2.5E-3
Vinyl chloride	5E-3
Arsenic	29E-3
Barium	679E-3
Cadmium	2.5E-3
Chromium	52E-3
Lead	5.7E-3
Mercury	0.1E-3
Selenium	2.5E-3
Silver	12.5E-3

Table 3-5: Leachate Composition for the Bioreactor Landfill (Sich and Barlaz, 2000)

Leachate Component[1]	Concentration (mg/L)
BOD	From 0 to 1 year : 7 000 From 1 to 3 years : linear decrease from 7 000 to 1 000 From 3 to 10 years : linear decrease from 1000 to 0 After 10 years : 0
COD	From 0 to 1 year : BOD/COD ratio = 0.8 From 1 to 3 years : BOD/COD ratio in linear decrease from 0.8 to 0.3 From 3 to 10 years : linear decrease to 100 mg/L After 10 years : 100 mg/L

[1]: All the other components are the same as for the engineered landfill (see Table 3-4)

The efficiency of the leachate treatment in the aeration pond is given in the following table (according to Sich and Barlaz, 2000). The amount of energy used by the aerator sets is calculated with the retention time in the aeration pond (50 days for all 4 treatment zones) and the power of the aerators (4 x 20 hp in zone 1, 4 x 15 hp in zone 2, 4 x 10 hp in zone 3 and 4 x 5 hp in zone 4).

Table 3-6: Leachate Treatment Efficiency for the Engineered landfill System (Sich and Barlaz, 2000)

Leachate Component	Efficiency (%)
BOD	92 CO_2 produced by BOD removal : 3.6 g/g BOD Sludge produced by BOD removal : 0.5 g/g BOD
COD	80
Total suspended solids	96
NH_3	21.6 (NH_3 is converted to NO_3)
PO_4	21.6[1]
Benzene	100[2]
Toluene	100[2]
Xylenes	100[2]
Ethylbenzene	100[2]
Chloroform	100[2]
Carbon tetrachloride	100[2]
Ethylene dichloride	100[2]
Methylene chloride	100[2]
Trichloroethene	100[2]

Leachate Component	Efficiency (%)
Perchloroethene	100[2]
Vinyl chloride	100[2]
Arsenic	85[1]
Barium	85[1]
Cadmium	85[1]
Chromium	85[1]
Lead	85[1]
Mercury	85[1]
Selenium	85[1]
Silver	85[1]

[1]: even if these compounds end up in the produced sludge, their amount is negligible compared with the sludge produced by the BOD removal.

[2]: all trace organic compounds are assumed to be volatilized during treatment.

The amount of water to be added to the bioreactor cell is calculated from the initial moisture content of the waste (set at 25 % w/w), the field capacity of the waste (set at 50 % w/w) and the precipitation rate. Only the amount of water needed to bring the waste to filed capacity during the filling phase was calculated, i.e. the waste is at field capacity at closure, even if water would still be required during the post-closure period because it is consumed by the methanogenesis and carried out of the cell by the saturated landfill gas.

3.4.6. *Landfill Gas*

The volume of landfill gas produced was calculated with the SWANA model:

$$G_t = W \frac{L}{s}\left(-(k+s)e^{(-k(t-t_i))} + ke^{(-(k+s)(t-t_i))} + s\right) \qquad (3.1)$$

Where:

- G_t : total volume of landfill gas produced (in m^3) at *t* time;
- W : the amount of waste in place (in tonnes) at *t* time;
- L : the landfill gas yield (in m^3/tonne of waste);
- s : first order rise phase constant (in yr^{-1});
- k : first order decay rate constant (in yr^{-1});
- t_i : lag time, i.e. time before the landfill gas production starts (in years).

The values of the model parameters are given in the following table (according to Sich and Barlaz, 2000).

Table 3-7: SWANA Landfill Gas Production Model Parameters (Sich and Barlaz, 2000)

Parameter	Value
W	At t = 1 year : 300 000 tonnes At t >= 2 years : 600 000 tonnes
L	Maximum yield : L_0 = 112 m^3/tonnes waste For the engineered landfill : L = L_0 x 40 to 70 % For the bioreactor landfill : L = L_o x 60 to 90 %
s	For the engineered landfill : s = 1 yr^{-1} For the bioreactor landfill : s = 0.3 yr^{-1}
k	For the engineered landfill : k = 0.03 yr^{-1} For the bioreactor landfill : k = 0.15 yr^{-1}
t_i	For the engineered landfill : t_i = 1.5 yr For the bioreactor landfill : t_i = 0.173 yr

The maximum landfill gas yield (L_0) was calculated from the waste composition (according to Chamard *et al*., 2000) and the specific waste components methane yields in m^3 CH_4/dry tonne (according to Sich and Barlaz, 2000) (converted to m^3 landfill gas/wet tonne using the moisture content (according to U.S. EPA, 2002) and the landfill gas composition (according to Sich and Barlaz, 2000)) given in the following tables.

Table 3-8: Waste Composition (Chamard et al., 2000)

Waste Component		Wet Weight Composition (% w/w)
A	Paper packaging	1.0
B	Newspaper, magazines and advertisements	18.3
C	Other paper	3.8
D	Cardboard packaging	5.2
E	Other cardboard	0.6
F	Composites	1.2
G	Sanitary fibres	5.4
H	Glass packaging	6.3
I	Other glass	0.4
J	Ferrous metal packaging	2.0
K	Aluminium packaging	0.7
L	Other metals	0.8

Waste Component		Wet Weight Composition (% w/w)
M	Food waste	18.5
N	Yard waste	22.3
O	Textiles	2.0
P	Plastic films	3.8
Q	Hard plastic packaging	2.2
R	Other plastics	1.3
S	Hazardous domestic waste	0.4
T	Small appliances	0.3
U	Furniture	0.3
V	Asphalt, construction & demolition waste, gypsum	0.6
W	Wood	0.7
X	Aggregates (sand, gravel)	0.2
Y	Other	1.7

Table 3-9: Specific Waste Component Methane Yield and Moisture Content (Sich and Barlaz, 2000; U.S. EPA, 2002)

Waste Component	Methane Yield (m^3 CH_4/dry tonne)	Moisture Content (% w/w)
Grass (assumed to be 50 % of N[1])	136	60
Leaves (assumed to be 30 % of N[1])	30.6	20
Branches (assumed to be 20 % of N[1])	62.6	40
Newsprint (assumed to be 50 % of B[1])	74.3	6
Office paper (assumed to be 100 % of A[1]+ C[1])	217.3	6
Coated paper (assumed to be 50 % of B[1])	84.4	6
Corrugated cardboard (assumed to be 100 % of D[1]+ E[1])	152.3	5
Food waste (assumed to be 100 % of M[1])	300.7	70
Sanitary fibres (assumed to be 100 % of G[1])	74.3 (assumption)	10 (assumption)
[1]: refer to the waste components in the previous table		

Table 3-10: Landfill Gas Composition (Sich and Barlaz, 2000)

Component	Concentration (ppv)
CH_4	0.55E+0
CO_2	0.45E+0
H_2S	3.55E-5
Benzene	1.92E-6
Toluene	3.93E-5
Xylenes	1.21E-5
Ethylbenzene	4.61E-6
Chloroform	3.00E-8
Carbon tetrachloride	4.00E-9
Ethylene dichloride	4.10E-7
Methylene chloride	1.43E-5
Trichloroethene	2.82E-6
Perchloroethene	3.73E-6
Vinyl chloride	7.34E-6

The volume of landfill gas collected, treated and released to the environment (fugitive landfill gas) was calculated taking into account the collection system efficiency.

Table 3-11: Landfill Gas Collection System Efficiency

Engineered landfill	Bioreactor Landfill
From 0 to 1 year : 0 % From 1 to 2 years : 50 % From 2 to 32 years : 80 % From 32 to end : 0 %	From 0 to 1 year : 50 % From 1 to 2 years : 75 % From 2 to 32 years : 90 % From 32 to end : 0 %

The landfill gas components' mass outputs from the systems were calculated from the volumes of collected and released landfill gas and the treatment method (flare, ICE or boiler) destruction efficiencies and emission factors, given in the following table (according to Sich and Barlaz, 2000). The partial oxidation of the landfill gas in the organic soil cover, represented by corresponding destruction factors (according to Sich and Barlaz, 2000), is also presented in the following table.

Table 3-12: Landfill Gas Treatment Method Destruction Efficiencies and Emission Factors (soil oxidation is also presented) (Sich and Barlaz, 2000)

Landfill Gas Component	Destruction Efficiency (%)			
	Flare	ICE	Boiler	Soil Oxidation
CH_4	99	99	99	15
H_2S	100	100	100	0 (assumption)
Benzene	99.7	86.1	99.8	15
Toluene	99.7	86.1	99.8	15
Xylenes	99.7	86.1	99.8	15
Ethylbenzene	99.7	86.1	99.8	15
Chloroform	98	93	99.6	0
Carbon tetrachloride	98	93	99.6	0
Ethylene dichloride	98	93	99.6	0
Methylene chloride	98	93	99.6	0
Trichloroethene	98	93	99.6	0
Perchloroethene	98	93	99.6	0
Vinyl chloride	98	93	99.6	0
Landfill Gas Component	**Emission Factors (kg/m^3 Landfill Gas Treated)**			
	Flare	**ICE**	**Boiler**	**Soil Oxidation**
CO	1,20E-2	7,50E-3	9,00E-5	
NO_2	6,50E-4	4,00E-3	5,33E-4	
Particulates	2,67E-4	7,67E-4	1,32E-4	
CO_2	1,05E+0[1]	1,06E+0[1]	1,07E+0[1]	1,62E-1[2]
SO_2	1,02E-4[3]	1,02E-4[3]	1,02E-4[3]	
HCl	9,61E-5[4]	9,12E-5[4]	9,77E-5[4]	

[1] : based on the carbon content of combusted constituents (minus carbon monoxide emissions)
[2] : based on the carbon content of oxidized constituents
[3] : based on the sulphur content of the gas
[4] : based on the chlorine content of combusted constituents

The energy recovered from the landfill gas in the case of the bioreactor landfill is calculated from the collected volume, the heat content of methane (assumed to be 890.7 kJ/mol, it was assumed to be the same in the gas as for the pure compound), the gas composition and the energetic efficiency of the production equipment (assumed to be

23 % for the ICE (assuming 10 % transmission and distribution losses) and 70 % for the modified boiler).

3.5. Data Validation

A data validity check was conducted during the data collection process. Validation may involve, for example, establishing mass balances and evaluating the data quality (ISO 14 041, 1998).

3.5.1. *Mass Balance Verification*

A mass balance comparing inputs (natural resources) and outputs (emissions) was carried out for the system. The detailed results of the inventory are available in Appendix G.

The results of the mass balance calculation are far from zero and would suggest incompleteness of the data used in the systems. However, this was expected considering the following:

- The emissions from the waste in the cell (landfill gas and leachate) do not have any inputs since the waste itself was not considered as a flow in the system. Therefore, the mass balances for the unit processes modelling them (Id. No. 5.1 to 5.2.3) are highly negative, i.e. the outputs are larger than the inputs (except for process 5.2.3, for which it is positive since the output is considered negative, i.e. an environmental credit);
- The mass balances for the non-road equipment and trucks are also negative, since the emissions to air (98% CO_2 for both types of processes) take into account oxygen (73% of the mass of CO_2) that is not included in the raw materials used by the processes (air is not considered since it is an abundant and renewable resource);
- The mass balances for the materials are affected by the same error as for the equipment and transportation processes but also by the fact that, in several of the generic data used to model the production of the materials employed in the system, water used usually in large amounts for energy production (hydroelectric), cooling, washing and other process related use or something else than a feedstock of the product is often considered as an input to the process but does not figure as an output. Another source of error in the mass balances calculated with inventory results generated with the Simapro 5 software is the fact that the mass of the materials produced by the unit processes considered is not included as an output, only emissions to air, water and solid waste are.

From these considerations, it appears that mass balance calculations are not a relevant way of verifying the validity of the data used in the models, at least not until higher quality generic data for the unit processes included in the systems is available (for which a particular effort at counting all inputs and outputs is made). The problem of the emissions from the waste in the cell will however remain, although it can easily be solved since it is a result of how the system was modelled.

3.5.2. *Data Quality Evaluation*

The data quality was assessed in a unique section (section 3.7.1). Appendix F presents the data quality results obtained for each process of the different options.

3.5.3. *Missing Data Considerations*

Some information gaps pertaining to the included unit processes and to the distance of transported material were filled by simplifying assumptions.

Numerous elements were, however, entirely excluded from the systems because of time constraints or lack of information. In the treatment of these omissions, the following considerations were made:

- Several excluded unit processes involved the use of energy to power pumps and compressors to move the leachate and landfill gas. The amount of energy they represent is probably very small compared to the amount of energy that has to be supplemented to the systems because of the collected landfill gas energy recovery in the case of the bioreactor;
- Since the removal and transport of the leachate treatment sludge, in the case of the engineered landfill, involves the same type of machines than for the various excavation included in the system (for the cell and ponds) but for a much smaller volume, it is probable that the material requirements and emissions associated with this activity are also much smaller, even if the transport distance involved is probably greater (also unknown). The emissions associated with the landfilling or other endpoint use of this sludge are however unknown and could have an influence on the results;
- The other excluded processes and life cycle stages concern activities shared by both options but differing in their intensity, which is proportional to the size of the cell. Since the engineered cell is assumed to be larger by definition than the bioreactor cell, all these processes would give the advantage to the second option. The omission of these processes may pose an interpretation problem if the inventory results and, more importantly, their associated potential environmental impacts, give the advantage to the engineered landfill.

3.6. Inventory Results

Inventory results are available in Appendix G in the form of tables generated by SimaPro 5 software (converted to MS-Excel format). These tables present total resource consumption, as well as all emissions associated with the system. These emissions are aggregated and classified by compartment, i.e. emissions to air, water and soil, solid (wastes) and non-material emissions. The inventory results are summarized in Table

3-14 and Table 3-15 and in Figure 3-1 to Figure 3-4. The life cycle stages Id. numbers indicated in the legend of the figures are the same as the ones indicated in the process flow diagrams presented in Appendix B.

The uncertainty associated with the effective landfill gas yield generates different inventory results according to the value considered. In the case of the engineered landfill, the fraction of the maximum landfill gas yield effectively produced varies from 40 to 70%. Since the gas is not converted to energy, only the unit processes dealing with the landfill gas emissions (Id. no. 5.2.1, 5.2.2 and 5.2.3) are affected by this variation in yield. These emissions are proportional to the volume of gas produced so it is only necessary to show the inventory results for the lowest and highest values of the effective yield fraction, 40 and 70%, to show the range of possible inventory results for the system.

In the case of the bioreactor landfill, energy is recovered from the collected landfill gas. The volume collected determines the amounts of energy recovered along with the volume to be supplemented to the system by external means, so more unit processes are affected by the value of the effective yield fraction (Id no. 5.2.1, 5.2.2, 5.2.3, 6.1 and 6.2). The landfill gas can be converted to electricity or heat, so heat and electricity have to be supplemented to the system. Since these two production processes do not have the same material requirements and emissions, the amount of energy produced in either form will change the inventory results. Thus, to show the range of possible inventory results for the system it is not only necessary to present the results for the lowest and highest effective yield fraction, but also whether the ICE or boiler is used.

The design calculation results are presented in the following table.

Table 3-13: Design Calculation Results for the Engineered and Bioreactor Landfills

	Engineered Landfill	**Bioreactor Landfill**
Cell Length (m)	354	327
Cell width (m)	177	164
Vertical wells		
Number of rows	2	--
Number of wells per row	6	--
Horizontal trenches		
Number of lifts	--	3
Lift 1 Height from bottom (m)	--	6
Number of trenches	--	16
Lift 2 Height from bottom (m)	--	12
Number of trenches	--	14
Lift 3 Height from bottom (m)	--	18
Number of trenches	--	15

The end of the study period corresponds to year 102 in the case of the engineered landfill (70 years after the end of the post-closure monitoring period) and to year 22 in the case of the bioreactor landfill (10 years before the end of the post- closure monitoring period).

3.6.1. *Raw Materials*

The most abundant raw materials used by both systems are the same: gravel, sand, soil natural gas and water, representing about 96% of the total. As can be seen, the first three are used in the leachate collection system's drainage layer (with a much smaller use by the horizontal trenches and vertical wells) and the final cover. The amounts used are proportional to the size of the cell and are greater for the engineered landfill, 1.41 x 10^8 kg compared to 1.26 x 10^8 kg for the bioreactor landfill. Natural gas is used by the two supplemented energy production processes and by some material production processes, the first two representing the major users (more than 98% of all natural gas consumed). Since some energy is recovered from the collected landfill gas from the bioreactor cell, the amount of energy supplemented to the system is less than that supplemented for the engineered landfill. The amount of natural gas used is also greater for the engineered landfill, 4.07 x 10^7 kg compared to an average of 2.38 x 10^7 kg for the bioreactor (it varies from 1.94 to 2.87 x 10^7 kg). The water is used by many products (geomembrane and pipes for example) fabrication processes (as process or cooling water). Since the amount of required products is again linked to the size of the cell, a greater amount of water is needed for the engineered landfill: 3.02 x 10^7 kg compared to 1.97 x 10^7 kg for the bioreactor. However, the volume of water that has to be added to the waste in the bioreactor cell in order for it to reach full capacity (a condition needed to accelerate the methanogenesis and waste degradation) is 1.23 x 10^5 m^3 or 1.23 x 10^8 kg at a density of 1000 kg/m^3. This input dramatically changes the material requirements of the system, an average increase of 70%, which becomes larger than that obtained for the engineered landfill.

3.6.2. *Emissions to air*

The most abundant air emissions are CO_2 and methane. The first takes three forms: biomass CO_2, CO_2 sink and fossil CO_2. The biomass CO_2 is associated with landfill gas and leachate (BOD) production, it is therefore more important for the bioreactor, ranging from 7.06 x 10^7 to 1.06 x 10^8 kg compared to 3.88 to 6.72 x 10^7 kg for the engineered landfill. However, since it is biogenic, it is not included in the greenhouse gases inventory (GWP) of the impact assessment phase. The CO_2 sink is also linked to the landfill gas production but it is the engineered landfill that has the advantage since it produces less gas, i.e. it stores more carbon in the waste that remains in the landfill because of non-ideal conditions, with 3.97 to 7.95 x 10^7 kg compared to 1.32 to 5.30 x 10^7 kg for the bioreactor. This avoided CO_2, even if biogenic, is however accounted for as a credit, i.e. a negative value, in the greenhouse gas (GHG) inventory since it is removed from the atmospheric system. The fossil CO_2 is primarily associated, at more than 95%, with the supplemented electricity and heat production using natural gas, the rest is produced by the various material production processes, non-road equipment and trucks. Since the engineered cell, requires more materials due to its larger size and since no energy is produced from its collected landfill gas, more fossil CO_2 is emitted from that system (9.75 x 10^7 kg compared to 4.69 to 6.73 x 10^7 kg for the bioreactor).

Methane is produced during the anaerobic degradation of the waste; it is the most important landfill gas component (0.55 ppv). Once collected, it is destroyed by combustion in the flare, ICE or boiler. The destruction efficiency of these different treatment methods is the same. However, the efficiency of the collection method is not the same for both types of landfill; the bioreactor's system is in fact more efficient (so as to maximize the energy recovery). The landfill gas is produced much slower in the engineered landfill, a larger fraction of it is produced after the end of the post-closure monitoring period and the pumping and treatment of the gas (in the case of the bioreactor, the end of the study period is reached before the end of the post-closure monitoring period so no landfill gas and methane are released after all activities on the site have stopped). These factors result in a larger quantity of methane being released to the atmosphere from the engineered landfill. Methane is also released to the environment during natural gas mining; this amount is proportional to the amount of energy generated from this gas. Since the engineered landfill is again supplemented with more energy than the bioreactor, more methane is released from the first system than the second. The methane released with the un-collected landfill gas (about 95% of all methane) and during natural gas mining represents 4.65 to 7.95 x 10^6 kg for the engineered landfill compared to 1.79 to 2.56 x 10^6 kg for the bioreactor.

3.6.3. *Emissions to Water*

The most important water emissions are dissolved solids, chlorides, sulphates, COD, suspended solids and oil, representing from 98% (engineered landfill) to more than 99% (bioreactor landfill) of all emissions to the water compartment of the ecosphere. All of them are associated with the supplemented energy production processes, the relative contributions of these processes ranging from 97 to more than 99% for these emissions. A notable exception is COD in the case of the engineered landfill, 66% of the emitted quantity is through the treated leachate outlet pipe to the receiving body of water. Directly related to the amount of energy supplemented, the emissions to water are more important for the engineered landfill, with values of 2.51 x 10^6 kg compared to 1.15 to 1.65 x 10^6 kg for the bioreactor landfill.

3.6.4. *Solid Emissions*

The solid wastes of the system are identified as unspecified solid waste, which represent from 94% of all solid wastes generated for the engineered landfill to more than 98% for the bioreactor landfill. These solid wastes are associated with the supplemented energy production and hence, are more important for the engineered landfill (4.16 x 10^6 kg) than for the bioreactor (1.96 to 2.80 x 10^6 kg). A noted distinction for the engineered landfill is the sludge produced by the leachate treatment, which amounts to around 5% of all solid wastes or 2.06 x 10^5 kg.

Table 3-14: Inventory Results Summary – Engineered landfill

Compartment	Mass Flows (kg)	
	40% Landfill Gas Yield	70% Landfill Gas Yield
Raw materials	2,20E+8	2,20E+8
Emissions to air	6,41E+7	1,36E+8
Emissions to water	2,51E+6	2,51E+6
Solid emissions	4,42E+6	4,42E+6

Table 3-15: Inventory Results Summary – Bioreactor Landill

Compartment	Mass Flows (kg)				
	60% Landfill Gas Yield – ICE	60% Landfill Gas Yield – Boiler	90% Landfill Gas Yield – ICE	90% Landfill Gas Yield – Boiler	Added Water
Raw Materials	1,78E+8	1,79E+8	1,71E+8	1,73E+8	1.23E+8
Emissions to air	8,48E+7	8,84E+7	1,44E+8	1,50E+8	--
Emissions to water	1,57E+6	1,65E+6	1,15E+6	1,27E+6	--
Solid emissions	2,71E+6	2,84E+6	2,01E+6	2,21E+6	--

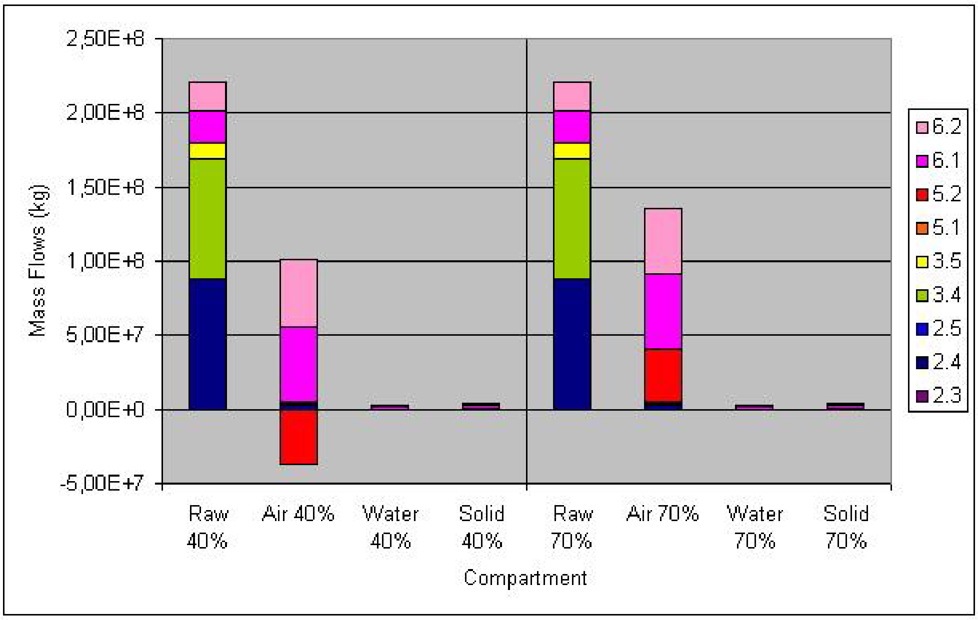

Figure 3-1: Absolute Contribution of Mass Flows for the Engineered landfill, by Compartments and Life Cycle Stages (see Figure 2-4), 40 & 70% Landfill Gas Yield.

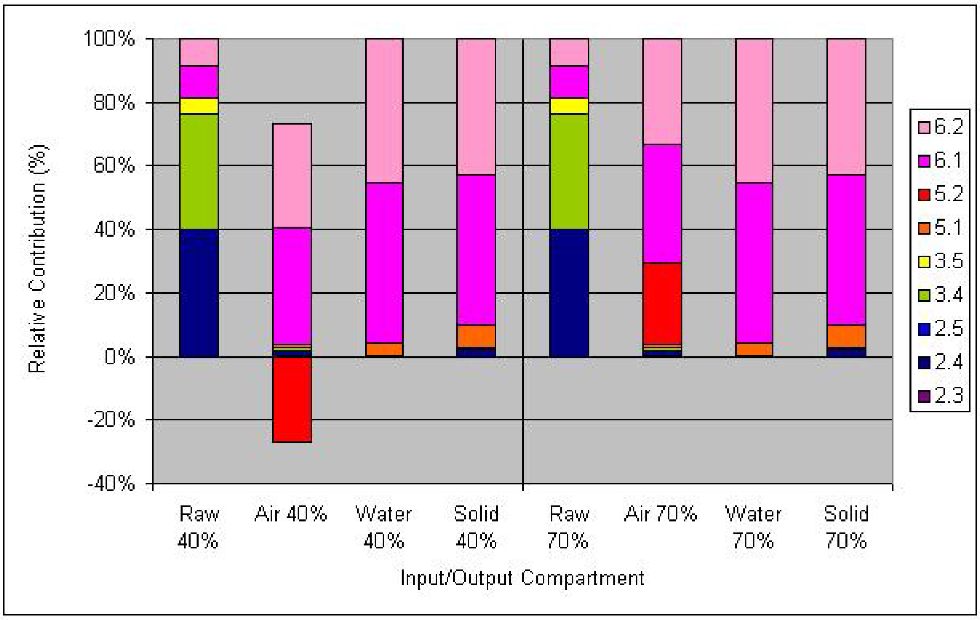

Figure 3-2: Relative Contribution of Mass Flows for the Engineered landfill, by Compartments and Life Cycle Stages (see Figure 2-4), 40 & 70% Landfill Gas Yield.

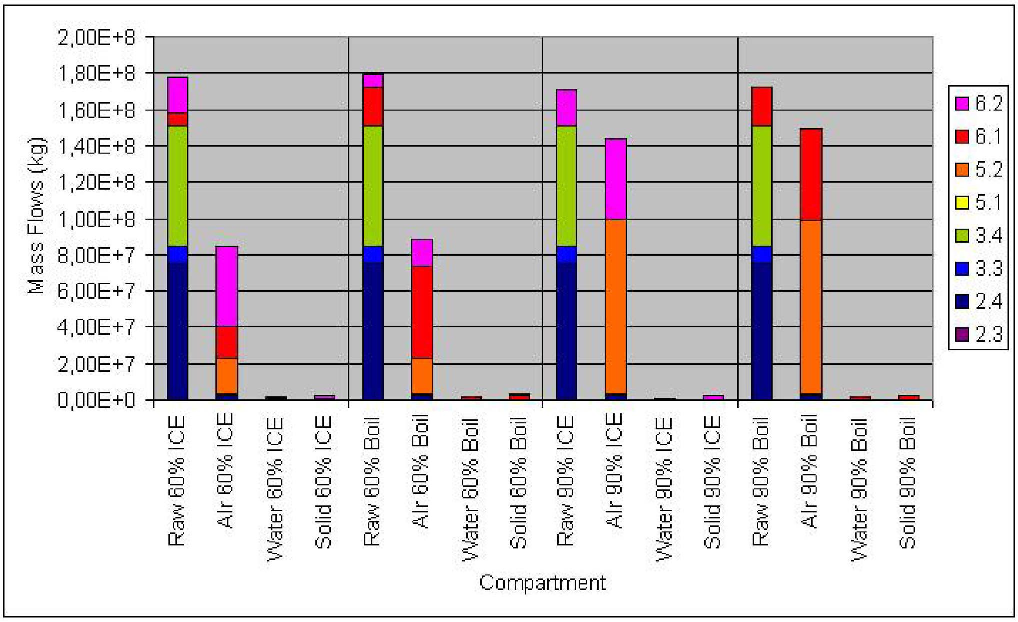

Figure 3-3: Absolute Contribution of Mass Flows for the Bioreactor Landfill, by Compartments and Life Cycle Stages (see Figure 2-4), 60 & 90% Landfill Gas Yield, ICE and Boiler.

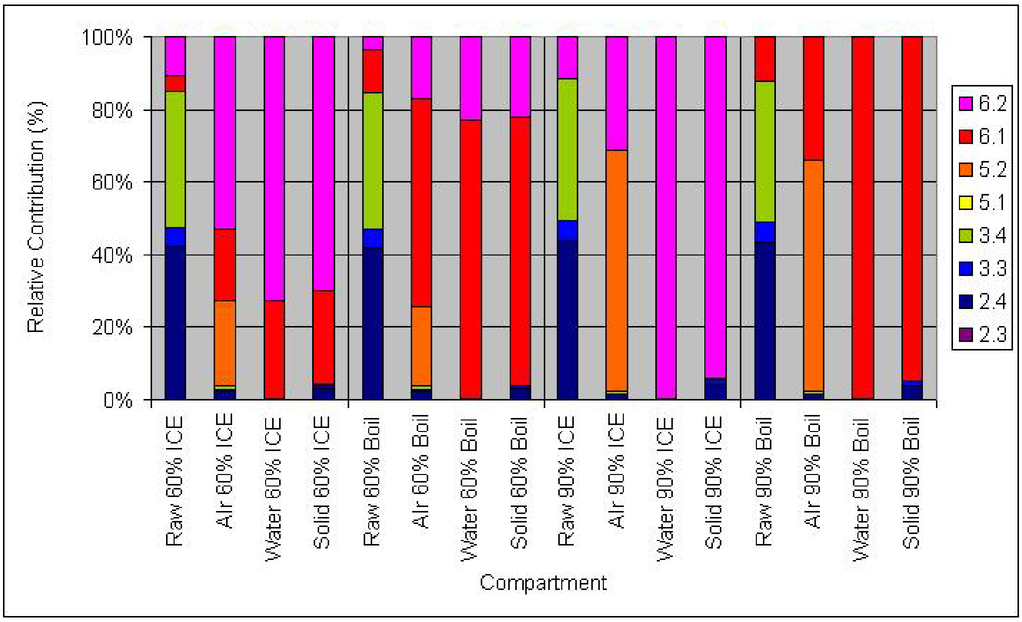

Figure 3-4: Relative Contribution of Mass Flows for the Bioreactor Landfill, by Compartments and Life Cycle Stages (see Figure 2-4), 60 & 90% Landfill Gas Yield, ICE and Boiler.

3.7. Inventory Analysis Limitations

The life cycle inventory results have been interpreted according to the goal and scope of the study. The interpretation includes a data quality assessment and an evaluation of the results' uncertainties.

3.7.1. *General Data Quality Evaluation*

The following section aims to assess the quality of data used in the inventory analysis. The reliability of the study's results and conclusions depends on the quality of the data used. Thus, it is important that these data follow the requirements specified in the goal and scope. The three parameters studied here are geographical, temporal and technological representativeness.

As stated in the progress report, the study was conducted with the data that could be obtained within the limited time available. This has had important consequences on the accuracy and precision of the data used, since it was impossible to obtain measured data from all production sites within the time frame of the study, and generic databases had to be consulted. However, the quality of the data used was sufficient to reach the goal of the study. Data quality requirements were as follows (Samson *et al*., 2002c):

- Temporal representativeness: The data used had to ideally not be older than five years unless it could be assumed that the unit process(es) it characterized had not changed since it was obtained.
- Geographical representativeness: The geographical zone from which data had to be gathered was North America.
- Technological representativeness: Data on technological performances of unit processes had to be representative of reality. The data had to correspond to technologies which were average in terms of environmental impact, giving a more realistic picture of what is available on the market. Thus, the mention average technology (A.t.) satisfied this requirement.

As previously mentioned in Section 2, in order to fill the requirements with regard to the geographical representativeness, the US EPA LCI data on waste management and the Franklin database, being specific to that zone, were preferred. However, due to the limited amount of data contained in these two sources, European databases were also used, thus creating a regional bias. The Canadian Database on Raw Materials, from the federal Ministry of Natural Resources, would raise the confidence of the results on the geographical standpoint; however the highly aggregated data it contains could not be used to conduct impact assessment since the emission categories used do not include characterization factors.

The methodology employed to qualify the data is relatively simple. Information (geography, time, technology) relating to each process was initially gathered. This information then made it possible to attribute a score according to the adequacy of the characteristics to the requirements mentioned above. Thus, if a process answered all the requirements, the given score attributed was 3. On the contrary, if none of the characteristics fulfilled the requirements, the attributed score was 0. The tables shown in Appendix F present the results obtained for each process of every option. Spaces left empty are either processes for which no data was available or processes regarded as negligible.

3.7.1.1. General Assessment

On a general basis, the data used do not fulfill the temporal requirements. Indeed, many data are more than five years old. However, it is important to note that for the data obtained from the Franklin database, the timescale is 1995 to 1999. Since the lower limit is older than 5 years, data taken from this database were considered as non representative. If 1997 had been used as a year under review, the temporal representativeness would be reached in the major part of the cases, and this, for both options. A nuance can also be made in regards to data temporal representativeness; certain processes undergo few modifications (energy consumption, raw material, liquid, gaseous and solid emissions) in time. Hence, data as old as 10 years could prove to be representative from the temporal point of view if this process did not undergo modifications with time.

According to this hypothesis, many data could become representative. In fact, certain types of elementary processes like diesel and energy production, transports, non-road equipments and emissions (processes 5.1 and 5.2) could be technologies that have been modified very little since 1995. The same conclusion can be given to sand, soil gravel and bentonite production. In that case, the temporal representativeness would be satisfactory. The same analysis could also be further extended to data older than 1995.

The requirements related to the technological representativeness were reached in the majority of cases (with an average of 80%), except when data were provided by the IDEMAT database. In this case, technology is formulated as an “average of all suppliers”. This mention does not meet the set requirements. Indeed, being given the confidential nature of these data, it is not possible to know the type of technology and the number of companies which generate the data.

Concerning the geographical representativeness, the data fulfilled the requirements in nearly 40% of the elementary processes. This is due to the use of data obtained from European databases.

3.7.1.2. Engineered landfill

The collected data do not correspond to the requirement concerning the temporal representativeness since no data from this option is younger than five years. As mentioned above, certain processes undergo few modifications in time. In this manner, 81% of the processes meet the temporal requirement (Appendix F). However, only the data obtained from IDEMAT database are older than 10 years which essentially includes materials (HDPE, PP, PVC). In respect to technology, data used satisfied the requirements for 81% of the processes. Once again, data obtained from the IDEMAT database infer a reduction in quality according to selected requirements. Finally, 42% of the data comes from North America. The data used in this option are therefore more representative on the technological aspect than on temporal and geographical aspects. If we consider the assumption concerning temporal requirement, the geographical aspect would be the most important point to improve.

3.7.1.3. Bioreactor Landfill

Similar conclusions given for the engineered landfill relative to representativeness can be drawn for the bioreactor landfill. This time, the general data quality obtained for this option slightly decreased. This is due to the fact that for bioreactor landfill, more processes were obtained from the IDEMAT database (processes 3.3).

This evaluation made it possible to acquire a rather general estimate of the inventory data quality. The evaluation criteria taken into account are the ones usually used within the LCA framework (i.e. temporal, geographical and technological representativeness). At this stage, it is possible to pinpoint the least representative data for which additional information should be obtained. Thus, it appears that the data obtained from the IDEMAT database are the most problematic when it comes to data representativeness. It would be useful to allocate more time to gather data of higher quality (precision, accuracy and representativeness), in order to further develop the landfill options and raise the confidence level of the conclusions of the present study.

3.7.2. *Accuracy of the Results*

It is impossible to calculate the uncertainties associated with the results of the inventory since all the data used to calculate it is of a deterministic nature, i.e. there are no error margins associated with the values given to the different mass flows in the generic data sets taken from the software databases or with the parameter values given by the several industry representatives contacted during the course of the data gathering. It is also very hard to evaluate qualitatively the uncertainties associated with the use of the generic data sets considered since the method used to collect this data is not very well documented, if at all, in the databases, nor was this information obtained from industry representatives.

What can be said, however, about the inventory is that it is not complete and does not cover every unit process included initially in the system boundaries. This is especially true for the material production processes that are modeled with generic data sets from commercial databases. It is impossible to find in these sources the exact production process for the considered product, most often a proxy production process has to be used and then only the material (HDPE, PVC, steel, etc.) can be modeled and not the manufacturing of the specified product (HDPE pipes or geomembrane for example). Many of the data sets available and used come from European databases and may, for some processes, not correspond to the Canadian reality; although some have been modified and adapted to the North American context by substituting energy production and transport processes that were included by their equivalent counterparts from the Franklin database.

4. LCA PHASE III: IMPACT ASSESSMENT

This section presents the third phase of the LCA study, which is the evaluation of environmental impacts. The general framework of this phase is composed of several mandatory elements that convert LCI results to indicator results (classification and characterization). In addition, there are optional elements for normalization, grouping or weighting of the indicator results (ISO 14042, 2000).

The present study includes the compulsory elements of the ISO standard, i.e. the classification and characterization, but does not include the normalization and weighting steps. The justification for these choices has been presented in Section 2.

4.1. Classification and Characterization

The first step in impact assessment consists in (ISO 14 042, 2000):

- Selecting the impact categories, category indicators and characterization models;
- Assigning the LCI results to the different impact categories selected (classification);
- Calculating the category indicator results (characterization).

As mentioned, the EDIP method included in the SimaPro 5 software was used for the present analysis, so its impact categories, category indicators and characterization models were used. These are presented in Section 2.

The software classifies the inputs and outputs inventoried for each option (LCI results) into the relevant impact categories and the relative contribution of these individual mass flows is determined for each impact category by equivalency factors (characterization factors). These factors, which allow for the conversion of LCI results to common units for each impact category, are presented in Appendix I. The converted results (named impact indicators), are presented for each landfill option in Appendix H.

The impact indicators were then added within each impact category and the outcome was a numerical indicator result which corresponds to the following equation:

$$IR_j = \sum_i q_i \times CF_{ji} \quad (4.1)$$

Where IR_j is the numerical indicator result for the *j*th impact category, q_i and CF_{ji} are the mass flow and characterization factor for the *i*th substance.

All the indicator results for the different impact categories make up the LCIA or environmental profile for the product system.

4.1.1. *Life Cycle Impact Assessment Profiles*

The detailed characterization results for both options are available in Appendix H in the form of tables generated by the SimaPro 5 software (converted to MS-Excel format). The environmental profiles are summarized in Table 4-1 and Table 4-2 and in Figure 4-1 and Figure 4-2; the impact categories have been divided according to their impact scale (see Table 2-1).

As can been seen in the figures, the potential impacts associated with both systems, in all categories considered, are dominated by those due to the landfill gas treatment and fugitive release emissions and the supplemented energy production (life cycle stages 5.2, 6.1 and 6.2). Only for the ozone depletion potential are the contributions due to the other life cycle stages above 20% (32% for the engineered landfill and an average of 25% for the bioreactor). In this case, the main substance involved is tertrachloromethane emitted during the production of fossil fuels and their use in non-road equipment, transport and energy production processes (the relatively large contribution of the leachate treatment stage in the engineered landfill system arise from the electricity consumption by the aerators used in the treatment pond; this energy is modelled as supplied with the Canadian electricity grid mix which includes 28% from fossil fuels).

4.1.1.1. Engineered landfill

In the case of the engineered landfill, the amount of supplemented energy is independent of the landfill gas effective yield, so the absolute contributions of these processes to all the impact categories are the same. The only categories for which their relative contributions differ are those for which the landfill gas related emissions have a dominant influence. As can be seen in Table 4-1, the total impact increases for these categories with the amount of landfill gas produced, collected, treated and released to the environment, so the relative contributions of the energy production decrease with the associated increase in the contribution from the landfill gas stage. The very important increase in global warming potential, which almost doubles, is directly linked to the increase in landfill gas production since not only does the emissions' volume increase by 80% but the credit for the carbon sink in the remaining waste is also reduced by 50%. As was mentioned above, the leachate treatment stage contributes to the ODP, but also to the eutrophication potential as it releases in the water compartment large quantities of ammonia and nitrates (3.44×10^7 and 9.46×10^6 kg respectively).

4.1.1.2. Bioreactor Landfill

In the case of the bioreactor landfill, the interpretation of the characterization results is complicated by the following facts: 1) the amount of energy needed to be supplemented diminishes as the landfill gas production increases and 2) the two supplemented energy production processes have different emission profiles and 3) the two landfill gas treatment methods considered have different destruction efficiencies and emission factors. The production of electricity from natural gas generates more potential impacts (as modelled in the system from generic data) than the production of heat from the same fuel. These greater impacts are not compensated by the smaller amount of electricity needed to be supplemented resulting form the lower production efficiency of the ICE compared to the boiler. The ICE is less efficient at destroying the trace compounds found in the landfill gas and generates more emissions than the boiler, so for the same amount of landfill gas treated, the associated impacts will be greater when the landfill gas is used to produce electricity rather than heat. The resulting impacts are a combination of these differences in generated impacts by the energy production processes, whether from the landfill gas or from natural gas.

The categories dominated by the supplemented energy production (ODP, ETWC, ETWA, HTW) show a greater impact for the boiler option, since the maximum amount of electricity has to be added to the system, which diminishes with the amount of landfill gas produced. The categories dominated by the landfill gas associated emissions (POCP, HTA and HTS) show a greater impact for the ICE option, which increases with the effective yield fraction. The remaining categories are a mix of these influences.

Since the end of the study period (22 years) is reached before the end of the post-closure monitoring period and the pumping of the landfill gas produced, a much smaller volume of gas is released to the environment for that option than for the engineered landfill, for which the temporal frontier is set at 102 years. This prevents the emissions of a large volume of methane (since this compound is very effectively destroyed by the ICE and boiler) and the contribution of this potent greenhouse gas to the GWP. This is the reason for the environmental credit observed for the system in the case of a 70% effective landfill gas production, the CO_2 sink being large enough to compensate the fugitive release of methane (this is not the case for the 90% effective gas production). The supplemented energy production being the other dominant process for this category, the boiler option presents the greater impact for the previously mentioned reason.

The acidification potential decreases with the landfill gas effective production, so it would tend to be dominated by the supplemented energy production; however the ICE option shows the greater impact. This is due to the ICE NO_2 emissions, as they are more important than the boiler's and compensate the reduction in energy production emissions.

The eutrophication potential shows different behaviour to the increase in effective landfill gas production. The increase in emissions (NO_2) due to the landfill gas treatment is compensated by the reduction in energy production emissions (NO_X) in the case of the boiler option but not the ICE option.

Heat production has much less emissions generating potential soil chronic ecotoxicity than electricity production (almost a 99% reduction), so the impacts to that category are dominated by the landfill gas emissions and the supplemented electricity production. The impact will therefore increase with effective landfill gas production for the boiler option since electricity always needs to be added to the system. The slight increase for the ICE option is due to the landfill gas emissions (especially toluene, representing 68% of the total impact) that more than compensate the fact that no electricity is needed since the system produces the maximum output for the system.

Table 4-1: LCIA Profile – Engineered landfill

Impact Category	Unit	40% Landfill Gas Yield	70% Landfill Gas Yield	Major Substances
Global warming (GWP)	g CO_2	1,36E+11	2,59E+11	CH_4, CO_2, CO_2 sink
Ozone depletion (ODP)	g CFC_{11}	1,34E+02	1,34E+02	Tetrachloromethane
Acidification (AP)	g SO_2	1,66E+09	1,67E+09	SO_X, NO_X, NO_2
Eutrophication (EP)	g NO_3	5,42E+08	5,50E+08	NO_X, NH_3, NO_2
Photochemical smog (POCP)	g ethene	4,45E+07	7,19E+07	CH_4, CO
Ecotoxicity water chronic (ETWC)	m^3/g	1,18E+10	1,18E+10	Cd
Ecotoxicity water acute (ETWA)	m^3/g	1,19E+09	1,19E+09	Cd
Ecotoxicity soil chronic (ETSC)	m^3/g	5,66E+06	7,65E+06	Formaldehyde, toluene, tetrachloroethene, benzene, xylene
Human toxicity air (HTA)	m^3/g	2,21E+12	3,54E+12	H_2S, benzene, CO, formaldehyde, vinyl chloride
Human toxicity water (HTW)	m^3/g	2,83E+08	2,83E+08	Cd
Human toxicity soil (HTS)	m^3/g	2,37E+06	4,10E+06	Vinyl chloride, benzene

Table 4-2: LCIA Profile – Bioreactor Landfill

Impact Category	Unit	60% Landfill Gas Yield – ICE	60% Landfill Gas Yield – Boiler	90% Landfill Gas Yield – ICE	90% Landfill Gas Yield – Boiler	Major Substances
Global warming (GWP)	g CO_2	5,67E+10	6,03E+10	9,90E+10	1,04E+11	CH_4, CO_2, CO_2 sink
Ozone depletion (ODP)	g CFC_{11}	7,67E+01	7,98E+1	6,07E+1	6,55E+1	Tetrachloromethane
Acidification (AP)	g SO_2	1,18E+09	1,15E+9	9,49E+8	9,05E+8	SO_X, NO_X, NO_2
Eutrophication (EP)	g NO_3	4,89E+08	3,72E+8	4,97E+8	3,22E+8	NO_X, NO_2
Photochemical smog (POCP)	g ethene	2,52E+07	1,73E+7	3,39E+7	2,19E+7	CH_4, CO
Ecotoxicity water chronic (ETWC)	m^3/g	7,59E+09	7,99E+9	5,56E+9	6,16E+9	Cd
Ecotoxicity water acute (ETWA)	m^3/g	7,57E+08	7,97E+8	5,54E+8	6,14E+8	Cd
Ecotoxicity soil chronic (ETSC)	m^3/g	2,95E+06	3,88E+6	2,94E+6	4,34E+6	Formaldehyde, toluene, tetrachloroethene, benzene, xylene
Human toxicity air (HTA)	m^3/g	1,42E+12	1,01E+12	1,87E+12	1,26E+12	H_2S, benzene, CO, formaldehyde, Pb
Human toxicity water (HTW)	m^3/g	1,84E+08	1,93E+8	1,35E+8	1,50E+8	Cd
Human toxicity soil (HTS)	m^3/g	1,45E+06	8,35E+5	2,16E+6	1,23E+6	Benzene, vinyl chloride

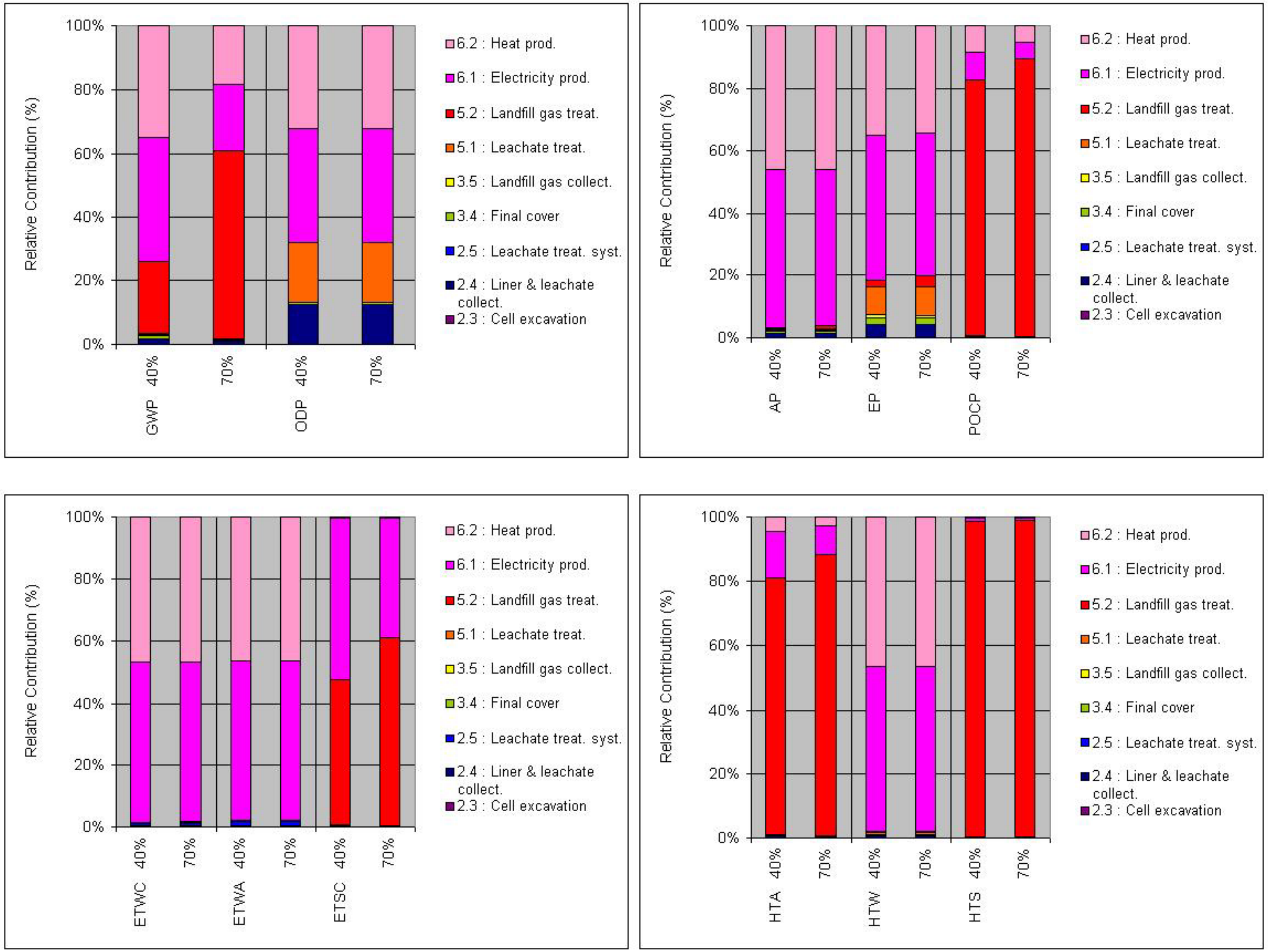

Figure 4-1: LCIA Profile for the Engineered Landfill, by Life Cycle Stages (40 & 70% Landfill Gas Yield).

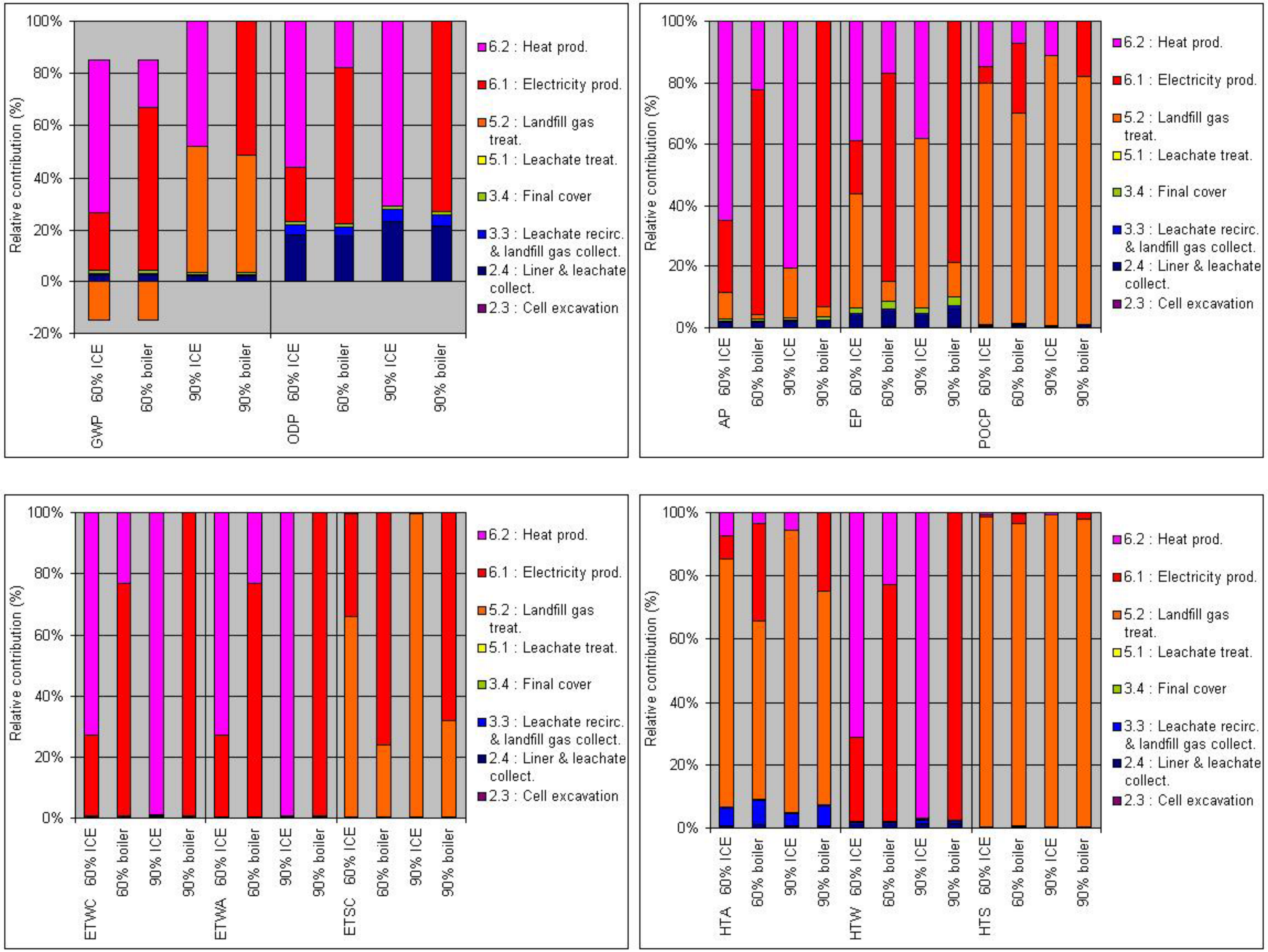

Figure 4-2: LCIA Profile for the Bireactor Landfill, by Life Cycle Stages (60 & 90% Landfill Gas Yield, ICE & Boiler).

4.2. Assessment of Data Gaps

The results presented in Section 4.1 are the results of calculations using characterization factors that were taken from the EDIP database provided with the software. The impacts they evaluate are only potential impacts since they model, thus simplify, the environment.

More importantly, the assessment of the characterization results includes the fact that some substances, identified during the inventory, do not have factors to convert them into the relevant units. They are undefined substances that the software does not recognize and cannot consider in its calculations. There are 46 such substances for the engineered landfill (17 airborne and 29 waterborne emissions) out of the 169 inventoried (33 raw materials, 67 airborne, 56 waterborne and 12 solid emissions and 1 non-material emission). There are 49 undefined substances for the bioreactor landfill (23 airborne and 26 waterborne emissions) out of 179 inventoried (37 raw materials, 77 airborne, 53 waterborne and 11 solid emissions and 1 non-material emission). These substances are reported in Appendix H. The absence of characterization factors can be explained by the fact that most undefined substances are identified not as a unique compound, but rather as a generic term that refers to a multitude of compounds, i.e. dust, particulates, organic substances; it therefore becomes very difficult to apply a unique conversion factor to the mix. This problem arises because the nomenclature and methodology used to build the inventory of unit processes found in generic databases are not yet standardized. Since these undefined substances are not considered in the evaluation of the potential impacts and because their exact nature cannot be known, their influence cannot be assessed precisely. The characterization results need therefore to be looked at carefully.

An examination of these undefined substances reveals that the same substances are shared by both options (they represent 99% of the total mass of the undefined substances). They are, in alphabetical order:

- For the airborne emissions: dust (SPM), methylenechloride, organic substances, particulates (PM10), particulates (unspecified), total organic gases;
- For the waterborne emissions: chlorides, COD, dissolved solids, oil, sulphate, suspended solids.

The first observation that can be made from theses results is that the undefined waterborne emissions are the most abundant ones in the inventories of both options, so the impact assessment is done while only considering the minor emitted substances. However, when the mass flows of the substances are examined, most undefined substances are emitted in larger amounts from the engineered landfill system and would, if they were given a characterization factor, give the advantage to the bioreactor landfill. The only exception is the particulates (unspecified) flow since it is associated in part with the treated landfill gas. The mass flow from the bioreactor is potentially 525% larger if the ICE is used, 4.61×10^4 kg compared to 1.04×10^4 kg for the engineered landfill. Indeed, the boiler emission factor being much lower than the flare's, the particulate emissions remain smaller than for the engineered landfill even when treating greater volume of gas.

5. LCA PHASE IV: RESULT INTERPRETATION

This section presents the final phase of the LCA study, the result interpretation, in which the results of the life cycle inventory analysis (LCI) and life cycle impact assessment (LCIA) are discussed as a basis for conclusions and decision-making in accordance with the goal and scope definition (ISO 14 043, 2000).

The objectives of this section are thus to analyze results, reach conclusions and explain limitations based on the findings of the preceding phases of the LCA study. The following elements are presented:

- Identification of significant issues based on the LCI and LCIA results;
- Result verification (completeness, sensitivity and consistency);
- Conclusions and recommendations.

5.1. Identification of Significant Issues

This first interpretation element consists in structuring the results from the LCI and LCIA phases in order to determine the significant issues, in accordance with the goal and scope definition (ISO 14 043, 2000).

The objective of the present study was to identify the landfill option which presents the least environmental impacts. Since each option has been analyzed in rather separate manner in the previous sections, it is now important to look at them in a comparative manner so as to identify the advantages and flaws of each and to select the most appropriate.

The first elements that can be compared are the intermediate materials (produced goods as opposed to raw materials) and the energy required by the two systems. These are presented in Table 5-1.

As observed from these results, the engineered landfill requires higher quantities of all types of inputs. Even when the values for the intermediate materials are translated into the values for the corresponding raw materials that they require (from 1.71E+8 to 1.79E+8 kg for the bioreactor versus 2.20E+8 kg for the engineered landfill) and the solid waste they generate (2.01E+6 to 2.84E+6 kg versus 4.42E+6 kg), the balance is still in favour of the bioreactor option.

Table 5-1: Material and Energy Requirements for the Two Landfill Options

System Inputs	Engineered landfill	Bioreactor Landfill
Intermediate materials (kg)		
Geosynthetic clay liner	2.57E+5	2.03E+5
Geomembrane	2.23E+5	1.82E+5
Geonet	3.52E+5	3.00E+5
Geotextile	2.89E+4	2.57E+4
HDPE pipes	2.65E+5	6.04E+4
PVC pipe	4.86E+2	--
Vitrified steel tank	--	3.40E+4
Aluminium dome	--	1.91E+3
Reinforced concrete base	--	3.00E+5
Gravel	6.32E+7	6.03E+7
Bentonite	1.58E+4	--
Sand	6.44E+7	5.38E+7
Organic soil	1.34E+7	1.12E+7
Diesel fuel	1.09E+5	8,87E+4
TOTAL MATERIAL	1.42E+8	1.26E+8
Energy (MJ)		
Hydraulic excavator	4.88E+5	3.90E+5
Track bulldozer	2.00E+6	1.72E+6
Vibratory roller	5.10E+4	4.26E+4
Drill rig	5.88E+4	--
Aerators	2.09E+6	--
Supplemented electricity	2.56E+8	from 0 to 2.56E+8
Supplemented heat	7.81E+8	from 0 to 7.81E+8
TOTAL ENERGY	1.04E+9	from 2.59E+8 to 8.68E+8
Trucks (for transport) (tonnes.km)	7.26E+6	6.43E+6

When considering the emissions from the systems to the air and water compartments of the ecosphere, it is better to consider the results of the impact assessment than those of the inventory (the biomass CO_2 is one of the most abundant airborne emissions, however it is not considered in the greenhouse gases accounting). To facilitate the comparison of all the characterized results, the normalized impact indicators for each category considered in the study are presented for both options in the Figure 5-1 (each indicator was given a score relative to the maximum average value for both options, with the maximum and minimum values of the indicators shown as error bars).

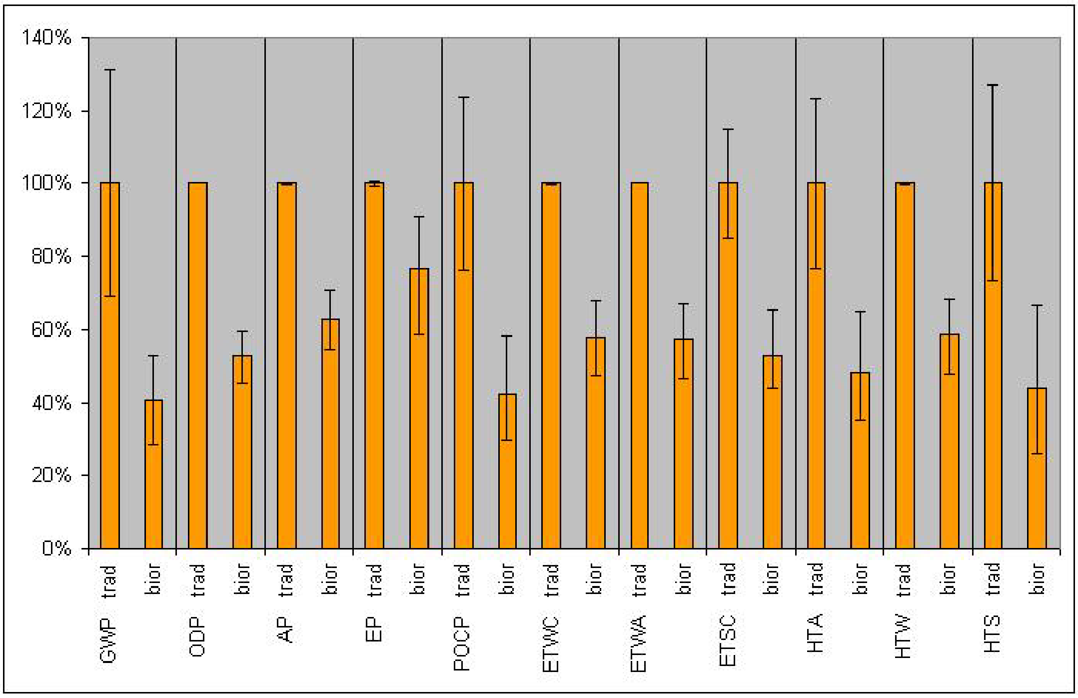

Figure 5-1: Relative Scores of the Impact Indicators for the two Landfill Options.

As can be seen in this figure, the impacts associated with the engineered landfill, even when considering the variability due to the uncertainty in the effective landfill gas production fraction, are higher for each of the impact category considered, than the ones associated to the bioreactor option.

The bioreactor is the system that requires the least raw materials, produces the least solid waste and generates the least impacts with respect to emissions. Hence, from the results of this study, it is possible to affirm that it is the most appropriate system from an environmental point of view.

5.2. Result Verification

The objectives of the result verification are to establish confidence in the results of the study and enhance reliability in them. The evaluation is undertaken in accordance with the goal and scope of the study and takes into account the final intended use of the study results (ISO 14 043, 2000). The following elements were evaluated:

- Completeness of the relevant information and data needed for the interpretation;
- Consistency of the assumptions, methods and data with the goal and scope for each product system under study.

5.2.1. *Evaluation of Completeness*

ISO states that "All relevant information and data needed for the interpretation should be available and complete. If any relevant information is missing or incomplete, the necessity of such information for satisfying the goal and scope of the study should be considered and as such, the preceding phases (LCI, LCIA) should be revisited, or alternatively, the goal and scope definition should be adjusted (ISO 14 043, 2000)".

These recommendations from the ISO standard were followed and led to the modifications that were brought to the Goal & Scope phase as documented in Appendix A. Time constraints and lack of information led to the exclusion of several life cycle stages and unit processes. However, it is expected that the excluded leachate and landfill gas collection processes (essentially the energy used by the pumps and compressors) and the landfill gas treatment processes prior to the energy recovery in the case of the bioreactor (dehydrators, compressors and pipeline transport) would have had a negligible influence on the results had it been possible to quantify them since they involve very small quantities of materials and energy compared to the rest of the systems. The other excluded elements involved processes either unique to the engineered landfill, i.e. leachate treatment sludge management, or that would have had greater material and energy demands and associated emissions for that option, since they are proportional to the volume of the cell. They would have therefore generated greater environmental impacts for that option and would have lead to the same conclusion in favour of the bioreactor.

5.2.2. *Evaluation of Consistency*

The consistency of the assumptions, methods and data with the goal and scope has to be verified. Moreover, for comparative studies, the equivalence of the systems have to be evaluated.

The function of the systems studied and the corresponding functional unit are the same for each option and so their performance can be considered equivalent. The system boundaries (geographical, temporal and technological) are either the same (geographical and technological) or were fixed using the same method, i.e. the temporal frontier was set as the time required to produce 95% of the calculated landfill gas yield. The unit processes included were, for the most part, the same or quantified in the same way. Likewise, the generic data used came from the same sources. Allocation was avoided for both options, by expanding the boundaries of the systems to include the energy production processes displaced by the energy recovered from the landfill gas in the case of the bioreactor. No inclusion criteria were used for the inventory flows, i.e. all flows identified in the generic data sets found in the databases were included in the systems. The same environmental impact evaluation method (EDIP) was used for all options.

All theses considerations ensured the equivalence of the systems analyzed in this study.

5.3. Conclusions and Recommendations

5.3.1. *Conclusions*

The main objective of this LCA study was to identify which landfill option between a engineered landfill and a bioreactor landfill would present the least environmental impacts.

When considering for each option, the function served, the defined system boundaries, the methodology and data sources used to build the inventory and the method to evaluate the potential environmental impacts, it can be concluded that the systems analyzed are equivalent and can be compared.

The engineered landfill requires more materials, energy inputs via the non-road equipment used and supplemented energy from external processes (natural gas electrical power station and industrial boiler) to achieve the same performance as the bioreactor landfill. The raw material inputs, solid waste outputs and emissions associated potential environmental impacts are also greater for the engineered landfill option (on average, 126, 182 and 185% that of the bioreactor, respectively). From these results, the bioreactor landfill can be identified as the preferred option from an environmental point of view.

The impact assessment identified the supplemented energy production as the dominant life cycle stage for both options (its average contribution to the impact indicator evaluated for each category considered is of 61% for the engineered landfill and 63% for the bioreactor), followed by the treatment and fugitive release of landfill gas (their contribution is of 33% and 32% for the engineered landfill and the bioreactor, respectively). This would tend to explain the advantage of the bioreactor option since, for that system, 1) energy is recovered from the collected landfill gas and this reduces the need for external energy and 2) landfill gas is produced at a greater rate, reducing the amount directly released to the atmosphere after the end of the post-closure monitoring period, the methane it contains (a potent greenhouse gas) being no longer destroyed (in fact the end of the study period is reached before the end of the pumping of the landfill gas).

Time constraints and lack of information led to the exclusion of several life cycle stages and unit processes. However, it is expected that the excluded leachate and landfill gas collection processes (essentially the energy used by the pumps and compressors) and the landfill gas treatment processes prior to the energy recovery in the case of the bioreactor (dehydrators, compressors and pipeline transport) would have had a negligible influence on the results had it been possible to quantify them since they involve very small quantities of materials and energy compared to the rest of the systems. The other excluded elements involved processes either unique to the engineered landfill, i.e. leachate treatment sludge management, or that would have had greater material and energy demands and associated emissions for that option, since they are proportional to the volume of the cell. They would have therefore generated greater environmental impacts for that option and would have lead to the same conclusion in favour of the bioreactor.

Certain considerations limit however the value of these conclusions.

- The number of design and operational parameters under investigation were limited to allow the research project to remain feasible with the allocated resources. Specifically, upstream processes (sorting, pre-treatment), which change MSW composition and state, and downstream processes (landfill fate after stabilization), were ignored. Further investigation may reveal these parameters to greatly influence the relative environmental performance of the assessed technologies;
- Since there is a lack of specific inventory data for North America and of time in which to do the study, a significant amount of data from European databases was used. This has definitely affected the results of the study. However, it is also important to mention that the data quality requirements for a comparative LCA intended for internal use only are not as stringent as for an LCA released to the public;
- An uncertainty analysis, which would give an indication of the robustness of the conclusions, could not be carried out with the allocated resources. Without knowledge of the degree of confidence one may have in the results, conclusions and recommendations drawn from the deterministic results may be unwarranted;
- The use of LCA results to support comparative assertions requires special attention since this application is likely to affect interested parties that are external to the LCA study. In order to decrease the probability of misunderstandings or negative effects on external interested parties, the present study shall be revised according to the ISO standards prior to public disclosure.
- The environmental evaluation of the options is based on models and so the calculated magnitude of the impacts identified represents only a potential outcome and simplification of reality (the divergence between models and reality is further increased by the fact that they are based on the European context). The justification of using such a method lies in the comparative nature of this study; all options being evaluated from the same reference base and using the same parameters so the bias is reduced. Hence, the results should not be taken out of this context and used as an absolute evaluation of the environmental impacts associated to either one of the options.

5.3.2. *Recommendations*

The recommendations presented here are issued specifically to address the lack of, or the consideration affecting, the validity of the results of the study.

Since energy consumption by the equipment used in the systems seem to have an appreciable influence on the associated impacts, i.e. the production of the electricity used by the aerators in the leachate treatment system, it would be important to evaluate the energy use of the different leachate and landfill gas collection and treatment equipment (pumps, compressors, dehydrators); especially since the volumes implicated are larger for the bioreactor.

It would be interesting to evaluate the influence of more than one parameter, i.e. the effective landfill gas yield fraction, on the study results. The efficiency of the capping, liner and landfill gas collection systems are only a few of the parameters that could be considered since they affect the amount of leachate and landfill gas released to the environment, which in the present system are lower for the bioreactor even if the volume produced and managed is greater than for the engineered landfill. The length of the post-closure monitoring period could also be examined since it also influenced the landfill gas emissions. A longer period would have reduced the amount of methane released by the engineered landfill. This could be done in conjunction with a variability study of these parameters and lead to an uncertainty analysis of the assessment results, which would increase the confidence in the conclusions reached.

It would finally be interesting to place this study in the larger context of municipal solid waste management from its collection to final disposal, which includes such activities as source reduction, recycling, composting and incineration.

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APPENDICES

Appendix A	Modifications Carried on Initial Goal and Scope Definition
Appendix B	Process Flow Diagrams
Appendix C	Unit Processes Characteristics
Appendix D	Calculation File
Appendix E	Process Cards
Appendix F	Data Quality Evaluation
Appendix G	LCA Inventory Results and Mass Balances Verification
Appendix H	LCA Impacts Assessment Results
Appendix I	Characterization Factors Used by the EDIP Method

APPENDIX A: MODIFICATIONS CARRIED ON INITIAL GOAL AND SCOPE DEFINITION

Appendix A is included in a separate file: modifications phase I.

APPENDIX B: PROCESS FLOW DIAGRAMS

Appendix B is included in a separate file: PFD.

APPENDIX C: UNIT PROCESS CHARACTERISTICS

Appendix C is included in a separate file: system summary

APPENDIX D: CALCULATION FILE

Appendix D is included in a separate file: calculations.

APPENDIX E: PROCESS CARDS

Appendix E is included in a separate file: process cards.

APPENDIX F: DATA QUALITY EVALUATION

Appendix F is included in a separate file: data quality evaluation.

APPENDIX G: LCA INVENTORY RESULTS AND MASS BALANCES VERIFICATION

Appendix G is included in a separate file: LCI results.

APPENDIX H: LCA IMPACTS ASSESSMENT RESULTS

Appendix H is included in a separate file: LCIA results

APPENDIX I: CHARACTERIZATION FACTORS USED BY THE EDIP METHOD

Appendix I is included in a separate file: EDIP factors.