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Quantitative Analysis of Critical Factors for the Climate Impact of Landfill Mining

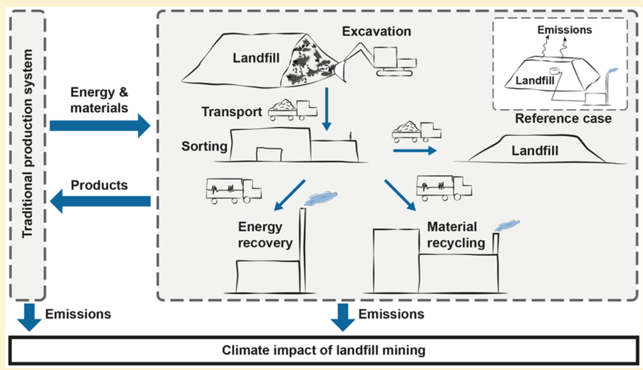
David Laner,*,† Oliver Cencic,‡ Niclas Svensson,§ and Joakim Krook§

†Christian Doppler Laboratory for Anthropogenic Resources, Institute for Water Quality, Resource and Waste Management, TU Wien, Karlsplatz 13/226, 1040 Vienna, Austria

‡Institute for Water Quality, Resource and Waste Management, TU Wien, Karlsplatz 13/226, 1040 Vienna, Austria

§Department of Management and Engineering, Environmental Technology and Management, Linköping University, SE-581 83 Linköping, Sweden

Supporting Information



ABSTRACT: Landfill mining has been proposed as an innovative strategy to mitigate environmental risks associated with landfills, to recover secondary raw materials and energy from the deposited waste, and to enable high-valued land uses at the site. The present study quantitatively assesses the importance of specific factors and conditions for the net contribution of landfill mining to global warming using a novel, set-based modeling approach and provides policy recommendations for facilitating the development of projects contributing to global warming mitigation. Building on life-cycle assessment, scenario modeling and sensitivity analysis methods are used to identify critical factors for the climate impact of landfill mining. The net contributions to global warming of the scenarios range from −1550 (saving) to 640 (burden) kg CO_2e per Mg of excavated waste. Nearly 90% of the results' total variation can be explained by changes in four factors, namely the landfill gas management in the reference case (i.e., alternative to mining the landfill), the background energy system, the composition of the excavated waste, and the applied waste-to-energy technology. Based on the analyses, circumstances under which landfill mining should be prioritized or not are identified and sensitive parameters for the climate impact assessment of landfill mining are highlighted.

■ INTRODUCTION

Historically, landfills have been the major way of waste disposal. Even in countries that have developed modern waste management systems, this disposal option has often remained important, or at least it was just a decade ago.[1] Therefore, most regions, for example, Europe and U.S., have a vast number of landfills of which many are old deposits and lack up-to-date sanitary technology.[2] These landfills are associated with long-term environmental impacts,[3] extensive aftercare periods[4] and land-use restrictions sometimes interfering with regional development. Landfill mining has been proposed as a strategy to address such implications while simultaneously recovering deposited raw materials.[5]

Apart from a number of reclamation projects throughout the world, solving traditional issues such as lack of landfill space and pollution concerns, full-scale landfill mining initiatives targeting the valorization of deposited materials and energy resources are rare.[6,7] While technology innovation and learning investments are drivers for the evolvement of any industry,[8] a growing amount of literature on this topic also advocates a policy as an essential requirement for making landfill mining applicable.[9,10] In Europe, landfill mining has increasingly become a policy issue involving discussions about new instruments for internalizing externalities (e.g., pollution prevention and recirculation of strategic metals) into private actors' returns as well as adjusted regulations removing current barriers for realization (e.g., landfill tax exemption for redeposition of generated residues).[5,6,11]

In this respect, the climate impact of landfill mining is of high relevance. Even if such projects could generate other positive environmental and societal impacts such as reduced human toxicity impacts and improved resource conservation,[12,13] their contribution to a prioritized policy target such as climate change mitigation is essential to motivate political action facilitating implementation.[10] So far, however, our understanding about the climate impact of landfill mining is limited to a few case-specific assessments.[12−15] While some of them conclude that landfill mining would lead to reduced climate impacts compared to business-as-usual,[12,14] others have found

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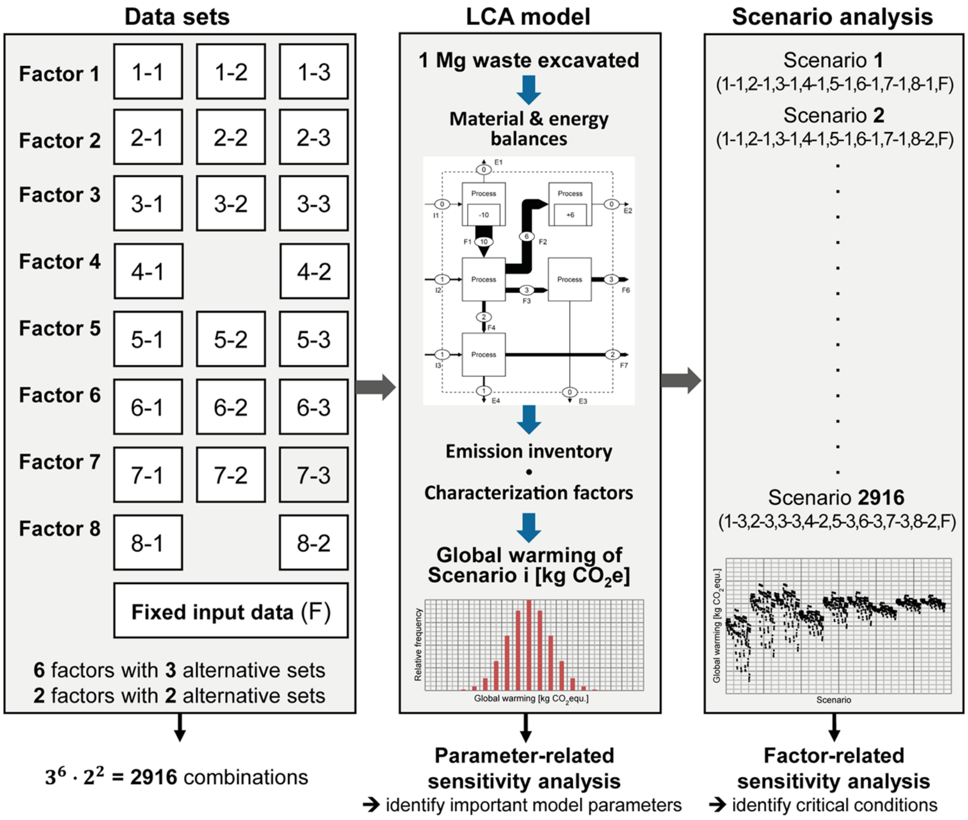

Figure 1. Schematic illustration of the set-based approach to investigate the importance of specific factors for the climate impact of landfill mining.

Table 1. Selected Factors to Be Considered by Different Alternative Parameter Sets in the Analysis of the Climate Impact of Landfill Mining[a]

	factor-type	description	alternative 1	alternative 2	alternative 3
F1	site-specific	waste composition	rich MSW landfill with high gas potential	average MSW municipal landfill with moderate gas potential	poor MSW landfill with low gas potential
F2	site-specific	aftercare and landfill gas management of reference case	no LFG collection	active LFG collection and destruction/oxidation	active LFG collection and utilization
F3	project setting	(excavation) and material separation	mobile separation unit	advanced separation plant	future potential
F4	intermediate project/system level	quality of separated material and raw material potential	low	–[b]	high
F5	intermediate project/system level	waste-to-energy (WtE) treatment	incineration, poor efficiency: electricity production only	incineration, average efficiency: heat and electricity production	incineration, high efficiency: heat and electricity production
F6	system condition	energy systems (heat and electricity)	heat and electricity mix with high fossils share	european average	heat and electricity mix with high renewables share
F7	system condition	primary material production systems	low efficiency and high fossil intensity	average production	high efficiency and low fossil intensity
F8	intermed. project/system level	required transport for recovered materials	small distances	–[b]	large distances

[a]Each alternative set for a specific factor designates a specific situation which could be encountered in a landfill mining project. [b]For factors 4 and 8 only two data sets are considered to reflect a realistic range without providing an average.

that such projects would instead result in net contributions to global warming.[13,15] These opposing results signify the complexity of landfill mining projects and that case-specific factors and settings play an essential role for the outcome of the evaluation. In order to support sound policies and strategic development of projects that contribute to global warming mitigation, more systemic knowledge about factors actually determining the climate impact of landfill mining is required.[6,16]

This study aims to assess generically important factors for the climate impact of landfill mining. In doing so, we develop a novel approach in which we combine life cycle assessment[17] (LCA), scenario modeling, and global sensitivity analysis for enabling a systematic and detailed analysis of the climate impact in a wide range of different landfill mining settings. The present study has the geographical and temporal scope of MSW landfills in Europe with current, state-of-the art management and treatment options. Based on the quantitative results, policy recommendations are developed in terms of strategies and measures for facilitating the development of projects that effectively contribute to reduced climate impacts.

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■ MODELING APPROACH

The modeling approach to establish different landfill mining scenarios and to investigate the climate impact of landfill mining is shown in Figure 1. First, we identify factors on the site, project, and system level that are potentially relevant for the climate impact of landfill mining project. Based on previous assessments,[13−16,18] eight such reoccurring factors reported to be of high relevance for the climate impact in specific landfill mining cases are defined (see Table 1). Two or three data sets are assigned to each factor to reflect a wide range of different circumstances and situations relevant for landfill mining projects. These data sets together with several constant input parameters (e.g., material properties such as the degradable carbon content in paper) form the input to a life cycle assessment model, which is used to calculate the contribution of a specific landfill mining scenario (=unique combination of alternative data sets) to global warming. Because there are six factors with three alternative sets and two factors with two alternatives, 2916 combinations are possible in total. The scenario results represent the possible range of global warming contributions for landfill mining projects under different conditions. Consequently, the variation of the scenario results related to the choice of alternative data sets of a factor is used to investigate the importance of this factor for the climate impact of landfill mining. Apart from the decomposition of the variation observed for the scenario results (= factor-related sensitivity analysis), the effect of varying single parameters on the variation of the results of a single scenario is also investigated. Therefore, all model parameters apart from physical constants (e.g., atomic weight) are defined to be normally distributed random variables given by mean value and relative standard deviation. The results for each scenario are calculated using Monte Carlo Simulation and provide the basis for identifying the most critical (single) parameters using sensitivity analysis (= Parameter-related sensitivity analysis). Overall, the modeling approach illustrated in Figure 1 produces 2916 scenarios each with 1000 single results from the Monte Carlo simulation. All calculations are performed in MATLAB.[19]

■ SELECTED FACTORS AND DATA SETS

Each of the eight factors in Table 1 consists of a set of model parameters and the corresponding data sets are defined building on data from previous studies on landfill mining in Europe and related literature on landfilling and waste treatment processes,[7,13−15,20−28] a comparison of life cycle inventory data for recycling systems,[29] and data from the ecoinvent database (version 3).[30] The various data sets for all of these factors are presented in the Supporting Information (SI) together with the data sources (see SI, Tables S-1−S-8).

Two of the factors are defined to be landfill-specific and involve (F1) the material composition, including its landfill gas potential, and (F2) the current (and alternative future) management of the landfill, particularly with respect to landfill gas. They constitute the foundation for any landfill mining project, influencing the potential of avoiding climate emissions from both landfill gas generation and replaced primary production through material and energy recovery. Based on previous field studies on 18 MSW landfills in industrial countries, three data sets were developed describing different landfill contents in terms of 10 material categories (see Table S-1 of the SI). These sets display landfills from varying time eras involving largely different material compositions covering reported ranges from the field studies. When it comes to landfill gas management, the developed data sets describe current European variations in practice, i.e. no gas collection, gas collection combined with flaring and gas collection combined with energy recovery. Together with the landfill gas potential of deposited waste, such varying practices determine the climate impact of the reference cases (i.e., "do-nothing scenarios").

On the project level, deliberate choices can be made regarding how to execute landfill mining. A key factor on this level is the employed technical processing schemes (F3), determining by what impact and to what extent the exhumed materials can be transformed into salable commodities to downstream material and energy companies. Here, three processing schemes were specified in terms of their resource inputs and separation efficiencies ranging from a conventional mobile unit, a state-of-the-art stationary processing plant to a best-available-technology (BAT) separation facility. The efficiencies of extracting, for example, metals and waste fuel by these different processing schemes vary from 40 to 90% and 30−90%, respectively (cf. Table S-3 of the SI).

The remaining five factors relate to the system level of landfill mining. In principle, they are external to the landfill mining project and can thus seldom be significantly influenced by the authority of an individual actor. Here, factors primarily relate to the generated and avoided climate impacts by replacing conventional primary production through valorization of separated material and energy resources. Two of them define the type and extent of avoided primary material production by recycling of, for example, different metals, aggregates and plastics. Factor F4 addresses variations in the market demand for the recovered materials and involves two data sets specifying to what extent they replace virgin raw materials. The alternative data sets enable the consideration of choices concerning the qualitative aspects of waste-derived raw materials and primary raw materials, which is reflected by different substitution factors. Such choices are often critical for the outcome of life cycle assessments of waste systems[31,32] and are therefore explicitly included via two alternative sets (low (20−60%) vs high (100%) substitution potential). For determining the type of avoided material production (F7), three data sets are developed accounting for production systems with varying efficiencies and fossil intensities of the energy supply, for example, related to regional differences. These largely different emissions profiles of primary production are together with the impacts of corresponding recycling processes used to define the net avoided climate impacts from material recycling.

The net climate impact of energy recovery of separated waste fuel is determined by the resource input and energy efficiency of Waste-to-Energy (WtE) plants and the conventional energy generation that is replaced. Although large future landfill mining projects may be able to employ advanced thermal treatment technologies,[5,18] the focus of this study is on existing technologies with full-scale process data readily available. Thus, employed WtE plants (F5) are described by three data sets which in principle represent the full variation in the net energy efficiency of current European waste incinerators, from rather inefficient power plants to BAT combined heat and power facilities. Similar as for avoided primary material production, the systems for conventional heat and power generation (F6) were specified in data sets ranging from a high fossil share, over the European average heat and electricity mix to systems that mainly are based on renewable energy carriers.

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In some of the reviewed environmental assessments,[16,33] transports of separated material and energy resources to downstream material and energy companies have been highlighted as potentially important for the climate impact of landfill mining. Two data sets (F8) were therefore developed to reflect differences in transportation distances. For some recovered materials, the variation in transports were due to current market structures generally set at relatively short distances 10−50 km (e.g., aggregates for use in earth constructions) while for others such as metals the data sets range from 250 to 500 km.

Apart from the data sets related to the eight factors described above, some inputs are the same for all the scenarios. These set-independent data sets include the physical properties of the excavated waste fractions (e.g., water content of organic waste, organic carbon content of paper, etc.), the physical constants (e.g., molar mass of CO_2), the management of redeposited materials (e.g., landfill gas collection rate), and the characterization factors used to quantify the global warming potential (e.g., GWP_{100} of 1 kg CH_4 is 28 kg CO_2 equivalents[34]) of an emission (see Tables S-9 and S-10 of the SI). Because the global warming characterization factor of methane of the latest assessment report[34] is higher than in previous assessment reports (before it was 25[35]) and because some of the data used in the analysis was extracted from existing studies (e.g., CO_2e-intensities of primary and secondary raw materials production), this causes direct CH_4 emissions to get a slightly higher weight relative to CO_2e-intensities from older studies. Although not in the focus of the present study, the effect of assumptions and methodological choices related to impact characterization factors, in particular the consideration of biogenic carbon emissions,[36] should be subject to further research and could be investigated using the set-based modeling approach presented in this study.

LCA MODEL

The contribution of landfill mining to global warming is calculated for a functional unit of one metric ton of excavated waste that would otherwise have been left in the landfill. The life cycle assessment model is based on mass and energy balances for the processes in the foreground system, that is, each fraction of the excavated waste (F1) is balanced throughout the processing steps via specific transfer coefficients.[37] Thus, outputs are a mix of different waste fractions and relevant properties (e.g., organic carbon content, water content, heating value, ash content) are determined based on the constituting fractions (cf. Table S-1 of the SI). After excavation, the waste materials are sorted and directed to further treatment and recovery processes (F3 and F5) or they are redeposited, which is particularly the case for soil material and fines. Consumption of fuel and electricity, transport, and auxiliary materials for plant operations are considered as burdens in the assessment. Savings are credited to the scenarios based on the substitution of products by waste-derived products via material recycling or energy recovery. System expansion is applied following a consequential approach using marginal technologies to account for multifunctionality. Functionally equivalent products are identified for the waste-derived products (e.g., primary aluminum is replaced by cast aluminum produced from aluminum scraps) and substitution ratios (reflected by F4) are applied to account for the savings achieved by resource recovery from waste due to the avoided production in the background system (F6 and F7).

The landfill gas potentials of the excavated waste and redeposited materials are derived from their composition, that is, the content of degradable organic carbon, using the default values suggested by IPCC for greenhouse gas inventories.[38] In the model, LFG emissions during excavation are neglected and LFG emissions occur only from the closed landfill (in the reference case) and the redeposited materials after sorting and upgrading. The landfill gas potential is calculated neglecting wood in the deposited waste, because lignin is practically not degradable under anaerobic conditions.[39] Consequently, carbon is bound by wood in anaerobic landfills and the corresponding amount of CO_2 removed from the cycle is credited to the landfill as saved emissions. In the model, the generated landfill gas consists of methane (50%) and carbon dioxide (50%), neglecting the presence of trace gases such as nitrous oxide or hydrocarbons. All carbon dioxide emissions from mineralization of biomass are accounted for as carbon neutral ($GWP_{100} = 0$) in the model as recommended by IPCC.[34] Also, some part of the generated methane is oxidized in the cover and converted to climate-neutral CO_2. For the reference case, the methane oxidation rate for noncollected landfill gas is 20% as recommended for closed landfill sites[20] (cf. Table S-2 of the SI).

Finally, the net contribution of landfill mining to global warming is calculated by subtracting the avoided impacts due to avoided direct (reference case) and indirect emissions (product substitution) from the impacts associated with the excavation, transport, treatment, and recycling of the waste. Hence, if the avoided impacts are greater than the additional impacts due to landfill mining, the net contribution of mining one ton of landfilled waste to global warming would be negative.

GLOBAL SENSITIVITY ANALYSIS

Factor-Related Sensitivity Analysis. In order to find out how the global warming contribution of landfill mining changes in response to variations of key factors and how these factors interact, global sensitivity analysis is used.[40,41] Therefore, the 2916 scenario results are explored with respect to the variation in factor data sets by apportioning the variance of the scenario results (output) to the variance of the eight (input) factors. In our case, factor variation is represented by the discrete choice of one out of two or three alternative sets and the effect of this choice is investigated for each factor and combinations of factors. The sensitivity of the output (the scenario result) with respect to varying specific factors is expressed by variance based sensitivity indices. The first order sensitivity index S_i is calculated according to eq 1 and represents the main effect contribution of an input factor to the output.[41] In eq 1, F_i is the i^{th} factor, $F_{\sim i}$ are all factors but F_i, Y is the model ouput, $E_{F\sim i}$ is the mean value of Y over all possible values of $F_{\sim i}$ while keeping F_i fixed. V_{Fi} is the variance of the mean values over the different sets of F_i, which is divided by the total (unconditioned) variance of the output (i.e., the variance observed for all scenario results). The enumerator in eq 1 can be interpreted as the expected reduction in output variance that would be obtained if F_i could be fixed.[40]

$$S_i = \frac{V_{F_i}(E_{F_{\sim i}}(Y|F_i))}{V(Y)} \tag{1}$$

The total effect sensitivity index S_{Ti} measures the first and higher order effects (interactions) of factor F_i. In eq 2 the enumerator is the first order effect of $F_{\sim i}$ (i.e., the expected

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reduction in output variance that would be obtained if all factors but F_i could be fixed), so that V(Y) minus this term gives the contribution in the variance decomposition of all terms containing F_i.[40]

$$S_{T_i} = 1 - \frac{V_{F_{\sim i}}(E_{F_i}(Y|F_{\sim i}))}{V(Y)} \quad (2)$$

While the first order sensitivity index measures the main effect of factor variation on the output variation, the total effect sensitivity index provides the overall importance of a factor for the output variation including interactions with other factors. These interaction-related effects are expressed by the higher order sensitivity index S_{Hi}, which is given by S_{Ti} minus S_i. In this study, these sensitivity indices represent the quantitative measures to express the importance of specific factors (on their own and in combination with others) for the climate impact of landfill mining.

Parameter-Related Sensitivity Analysis. In addition to the factor-based analysis, the effect of varying single parameters on the scenario results is investigated to identify the most important model parameters within the LCA model over all scenarios. Apart from physical constants (e.g., atomic weight), all model parameters are defined to be normally distributed random variables given by mean value and a fixed relative standard deviation (rsd) of 10%. The same rsd is used for all parameters, because the Monte Carlo Simulation results are not supposed to reflect the probable range of variation of model outcomes (this is the aim of the scenario analysis), but to identify the most important model parameters without considering their actual uncertainty. On this basis, model parameters that should be determined with the highest accuracy in a specific landfill mining case, are identified. Due to the large number of scenarios, a screening procedure based on stepwise regression modeling is developed to evaluate the sensitivity of model outcome with respect to the individual model parameters. For every scenario a multilinear regression model is established to explain the variation observed in the scenario outputs (1000 Monte Carlo Simulation runs) by linear combination of input parameters.[40] Parameters are included in the final model, if the p-value is below 0.05, that is, the null hypothesis that there is no relationship between parameter variation and model output is rejected at a 95% confidence level. The model coefficients of determination R^2 are calculated for the final regression models (one model for each of the scenarios) to investigate the nonlinearity of the model and range between 0.96 and 0.99 (cf. Figure S-1 of the SI). This underlines the suitability of regression analysis to investigate the effect of input parameter variation on the scenario outputs.[40] Finally, the parameters of the regression models are analyzed concerning how often they are included in the final models (max. 2916) and their mean regression coefficients over all scenarios. Finally, it should be emphasized that regression analysis is used on a screening level to identify parameters of major importance in the model. The importance of model parameters in specific scenarios or archetype settings would be the subject of a more detailed analysis that needed to go beyond aggregating parameter regression statistics over all the investigated scenarios.

RESULTS

Scenario-Based Sensitivity Analysis to Identify Critical Factors. The analysis of the results exhibits an average net climate impact of landfill mining over all scenarios of −81.1 kg CO_2e per Mg of excavated waste (Figure 2). However, the

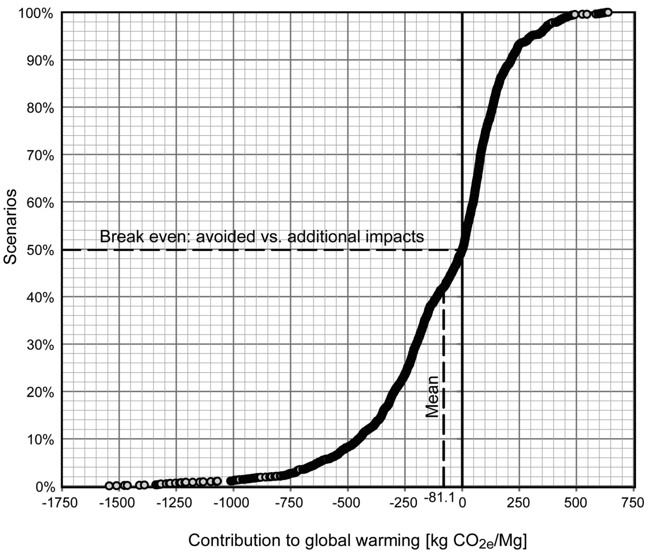

Figure 2. Cumulative distribution of the 2916 scenario results.

shares of scenarios with positive or negative net contributions to climate change are practically equal and the median of the scenario results is 1 kg CO_2e per Mg of excavated waste. Therefore, the positive or negative contribution of a landfill mining project primarily depends on the realization of specific factors with scenario results ranging from the best case of a net saving of 1550 to the worst case of a net burden of 640 kg CO_2e per Mg of excavated waste. This is also the range of global warming contributions observed by previous landfill mining studies.[12,14,15] Overall, 90% of the scenario results are located within the interval from −630 to +305 kg CO_2e per Mg of excavated waste.

According to the variance based sensitivity analysis (Table 2), the most important factor for the scenario results is the reference case (F2). This is the definition (reference scenario) of what would have happened, if the landfill had not been excavated. Varying this factor has mostly first order effects on the net climate impact, because the avoided emissions are mainly related to landfill gas that would be released directly to

Table 2. Variance Based Sensitivity Indices Quantifying the Main Effect of Factor Variation (S_i), the Interaction Effect of Factor Variation (S_{Hi}), and the Total Effect of Factor Variation (S_{Ti}) on the Scenarios Results[a]

factor	S_i (first order effects)	S_{Hi} (higher order effects)	S_{Ti} (total order effects)
F1	0.018	0.190	0.207
F2	0.448	0.057	0.506
F3	0.023	0.087	0.110
F4	0.025	0.011	0.036
F5	0.051	0.090	0.142
F6	0.148	0.172	0.320
F7	0.004	0.011	0.016
F8	0.000	0.001	0.001
total	0.717	0.619	1.336

[a]Note that double counting of factor-interaction effects causes the sum of S_{Ti} indices to exceed 1.

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the atmosphere to different degrees depending on the chosen data set. The second most important factor is the background energy system (F6), which is relevant in relation to the energy used by landfill mining, but especially with respect to energy recovery from waste replacing electricity and heat generation in the background system. For this factor, the first and higher order effects are of similar importance, because varying the data set for the background energy system affects the scenario results directly and in combination with other factors such as content of combustibles in the landfill (F1), separation efficiency of waste fuel (F3), and employed WtE technologies (F5). Such higher order effects are in fact even more prominent with respect to variation of the composition of the landfill (F1). Other factors, whose variation also has significant effects on the observed variation of the scenario results, are the applied waste-to-energy technology (F5) and the choice of sorting and upgrading technology (F3). The limited importance of variation in factors related to avoided impacts by material recycling (i.e., substitution factors (F4) and background material production systems (F7)) can be explained mainly by the low occurrence of resource-intense materials in MSW landfills (e.g., metals) and to some degree by the grouping of primary and secondary production in the same data sets (i.e., both clean, both average, both dirty, see Table S-11 of the SI and the related discussion). Finally, transport distances for recovered materials (F8) reflecting plausible ranges within Europe are irrelevant for the variation in scenario results.

In Figure 3, the scenario results are grouped with respect to the four most critical factors (highest total order effects) that

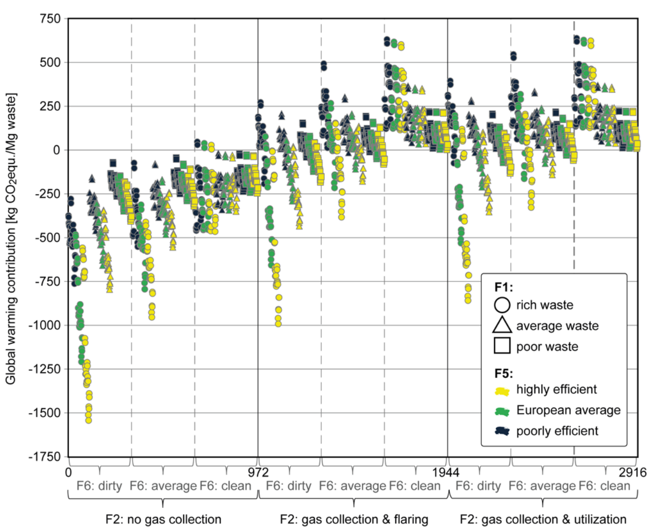

Figure 3. Scenario results grouped according to the four most important factors: F2−reference scenario, F6−background energy system, F1−landfill composition, F5 − Waste-to-Energy technology. Reading example: The highest net savings of CO_2e (yellow circles in the left lower corner of the figure) are achieved by scenarios including set 1 (no gas collection) of factor 2 (reference case), set 1(dirty) of factor 6 (background energy system), set 1 (waste rich in organics and metals) of factor 1 (waste composition), and set 3 (poorly efficient) of factor 5 (energy recovery technology).

together explain almost 90% of the scenario results' variance. It is apparent, that the reference case (F2) has a dominant effect on the scenario outcome. Here, the main condition is whether the landfill involves gas collection or not, while if the collected gas then is used for electricity generation or just oxidized is less important. When it comes to the background energy system (F6), an increasing share of renewables clearly pushes the scenario results toward net global warming contributions. In relation to this, energy recovery with CHP plants is generally preferable (F5: European average and F5: highly efficient) from a climate perspective and the employment of such facilities is a necessity for obtaining the highest net savings. Such clear tendencies are however not as apparent for even more interactive factors such as the landfill composition (F1). In particular, this specific factor has a significant effect on the overall spread of the scenario results, as set 1 of F1 (F1: rich waste) is part of both the best and worst scenarios regarding the net climate impact of landfill mining (circles in Figure 3). On the one hand, this is due to the high potential savings in case of recovery of the materials contained and their biodegradable fraction (i.e., avoided landfill gas in the reference case). On the other hand, it is also because of the relatively high net climate emissions caused by the incineration of fossil plastics in highly renewable background energy systems and lower direct emissions in case of proper landfill gas management. For old landfills with already well degraded waste (F1: poor waste, indicated by boxes in Figure 3) the spread of results is much lower, indicating only limited potential for net savings as well as net burdens when mining such landfills. As illustration, particularly unfavorable settings for landfill mining are constituted by active landfill gas management (F2: gas collection and flaring and F2: gas collection and utilization), a clean background energy system (F6: clean), a landfill rich in organics and metals (F1: rich waste), and a WtE plant with relatively low efficiency (F5: poorly efficient). Although, the variation of the factors F3, F4, F7, and F8 has a much lower effect on the scenario results, tendencies can also be identified for these factors especially in regards to sorting and upgrading technology (see Figure S-2 and Table S-11 of the SI). Similar as for the landfill composition, employing more intensive separation (F3−2 and F3−3) schemes increases the spread of scenario results. Dependent on the realization of the other factors intensified sorting might result in both, higher savings (e.g., if waste is mined from a rich landfill (F1−1) and upgraded to a high material quality (F4−2)) and higher burdens (e.g., poor landfill located (F1−3) in a clean background energy system (F6−3)).

Critical Parameters of the LCA Model. Parameters included in more than 70% of the regression models are shown in Table 3 together with their mean regression coefficients (average over all models). Out of the 33 parameters in Table 3, one-third is directly related to the generation and management of LFG in the reference case and the LFG emissions associated with the redeposition of landfill mining residues. Landfill gas emission parameters such as the methane oxidation rate, LFG collection and destruction rates, LFG reduction factor and collection efficiency for redeposited materials, are also those which are included in all regression models (100% inclusion rate, cf. Table 3), which highlights their crucial importance for the climate impact of landfill mining. For instance, doubling the methane oxidation rate in the landfill top cover (which is the same for all the alternative data sets of F2) from 20% to 40%, which may be realistic for some settings,[42] would result in an increase of the average net climate impact of landfill mining over all scenarios by 59.4 kg CO_2e per Mg of excavated waste (see Figure S-3 of the SI).

Another important group of parameters (again $^1/_3$ of the list in Table 3) is primarily related to the valorization of extracted

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Table 3. Parameters of the Various Factor Sets That Had a Significant Effect on the Model Result in Most Cases (Included in at Least 70% of the Regression Models). The mean regression coefficient (β)[a] is shown together with the parameters to provide an indication of the effects' direction (negative: the higher the parameter value, the lower the contribution to global warming, positive: the higher the parameter value, the higher the contribution to global warming)[b]

parameter	% included	mean β	parameter	% included	mean β
Factor 1: Composition of Excavated Waste					
content of soil and fines	92%	96	content of organic matter	87%	−645
content of paper	91%	−1389	content of plastics	87%	730
content of Al metals	90%	−5228	content of stones/inerts	72%	122
content of wood	88%	640	content of Fe metals	71%	−36
Factor 2: Reference Case ("Do-Nothing Scenario")					
methane oxidation rate	100%	297	LFG collection rate	67% (100%)[c]	358
methane content in LFG	96%	−260	destruction rate of collected LFG	67% (100%)[c]	272
Factor 3: Sorting and Upgrading					
TC for paper to combustibles	84%	−42	TC for paper to residues	77%	126
TC for plastics to combustibles	78%	62			
Factor 4: Substitution Factors					
LFG potential reduction factor	100%	104	substitution factor for Fe	83%	−64
substitution factor for Al	98%	−52			
Factor 5: Waste-to-Energy Technology					
net electricity efficiency	88%	−520	net heat efficiency	56% (84%)[c]	−167
Factor 6: Energy System					
CO_2e of electricity production	77%	−402	CO_2e of heat production	58% (86%)[c]	−1142
Factor 7: Raw Material Production System					
CO_2e of primary Al	98%	−3	CO_2e of primary steel	83%	−19
CO_2e of tkm transport	85%	146			
Factor 8: Transport Distances					
none					
Fixed Factors (Only One Set of Parameters)					
GWP of $CO_{2,\mathrm{fossil}}$	100%	169	C_{org} of paper	91%	−216
LFG collection efficiency for redeposited material	100%	−187	LFG potential of fines	88%	−0.1
C_{org} of plastics	98%	220	heating value of plastics	77%	−3
GWP of CH_4	97%	−5	C_{org} of degradable organics	70%	−149

[a]Each linear regression model takes the general form $y = ß_1x_1+\cdots+ß_nx_n+\varepsilon$, where y is the model outcome, x_i is a specific model parameter, $ß_i$ is the regression coefficient of this parameter, and ε is the error term. The mean regression coefficient is calculated over all regression models that include the respective parameter. Note that the comparison of ß values among parameters is not straightforward due to different parameter units and different parameter inclusion rates across scenarios. [b]Abbreviations: LFG··· landfill gas, TC··· transfer coefficient, CO_{2e}... CO_2 equivalents, tkm··· ton-kilometer, GWP··· global warming potential [c]Parameter is due to model structure not included in all scenarios. The percentage in brackets relates to the fraction of scenarios, where the regression model could possibly include the parameter.

materials and energy resources. For material recycling, important parameters on the system level specify the avoided GHG emissions through replaced primary production of aluminum and steel. On the site-specific and system levels, the contents of metals in the waste and the quality of the metal scrap fractions (substitution factors) are of particular importance. With respect to the model parameters related to energy recovery, the content of combustibles in the waste, the efficiency of sorting out combustible fractions, the net efficiency of the waste-to-energy plant, and the GHG emissions of replaced conventional energy generation are critical for the resulting climate impact. With respect to combustibles, sorting out more plastics results on average in additional burdens and sorting out paper in savings. The latter due to a higher share of climate neutral CO_2 emissions from incineration and decreased landfill gas production from redeposited residues.

Although the model parameters can be grouped according to their major process affiliation, several parameters, particularly on the site-specific level, affect the model results via different mechanisms and are therefore not straightforward to interpret. For instance, the content of paper and the content of biodegradable organic matter in excavated waste influence the net climate impact in various ways, that is, they affect the LFG potential of the waste (avoided emissions due to LFG emissions of the reference case), the amount of potentially extractable renewable fuel (avoided emissions due to energy recovery and substitution), and the LFG potential of landfill mining residues to be redeposited (added emissions). Therefore, the mean regression coefficient associated with the parameters indicates the main (average) effect of parameter variation on the climate impact. For example, the content of biodegradable organic matter contributes on average to avoided climate impacts. Thus, it is to a larger extent related to the LFG potential of the reference case and the renewable share of the exhumed waste fuel (avoided emissions) than to the LFG potential of redeposited residues (added emissions).

It should be noted, that Table 3 includes only the parameter most frequently present in the regression models for all scenarios. Hence, for specific scenarios several other parameters may also be of major importance for the climate impact of landfill mining. However, the ones presented here are most likely of high significance also in these cases and should be determined with high accuracy in any landfill mining project to

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allow for a reliable evaluation of its contribution to global warming.

DISCUSSION

As demonstrated in this study and in line with previous case studies,[12−15] the climate impact of landfill mining can vary considerably from case to case, ranging from large emission savings to significant net contributions to global warming. General policies supporting landfill mining based on this criterion are thus not an option, but instead such measures should be accompanied by specific guidelines and obligations regarding the selection and development of suitable projects. Our results pinpoint several generic factors determining the climate impact of landfill mining on MSW deposits and these findings are here used to draft some tentative principles for facilitating projects contributing to reduced impacts.

First, the selection of landfills for mining is of key importance for being able to develop projects that result in a reduced climate impact. A general principle is to prioritize landfills with currently no or poor LFG management systems in place, because such scenarios are associated with net avoided GHG emissions in virtually all cases (cf. Figure 3). Although many of the other scenarios on landfills having installed gas collection systems also result in net avoided climate emissions, such projects should as far as possible be avoided in regions with highly renewable energy systems. In such settings, landfill mining is very probable to generate a net contribution to global warming regardless of how rich the MSW deposit is in recyclables or how efficiently the valorization of these deposited materials and energy resources is executed. When it comes to the landfill content, prospecting efforts should target deposits containing high shares of metals and anaerobically degradable organic materials (e.g., organic waste, paper), because the latter are directly related to the LFG potential of the waste as well as because they enable the extraction of waste fuel with a high share of renewables. Furthermore, deposits containing high amounts of soil material and fines, plastics and wood are in general less favorable to mine from a climate perspective. There are several reasons for that. What these materials all have in common is that they reduce the climate impact of the reference case due to their low or even nonexisting LFG potential. A high share of soil material and fines also often correlates with relatively low amounts of recyclables and related potential climate savings in terms of avoided primary production. When it comes to plastics, their occurrence increases the share of fossil CO_2-emissions from WtE, especially in situations where material recycling of plastics is not an option.

In principle, landfill mining projects should be implemented using as advanced material sorting technologies as possible to maximize potential GHG savings from material recycling and energy recovery. In contrast to material recycling, however, it is not self-evident that an efficient separation of all deposited combustibles into waste fuel is beneficial from a climate perspective. The regression modeling shows that the mean impact of separating both wood and plastic into waste fuel is associated with net burdens. Here, the combination of landfills rich in plastics that are located in regions with renewable energy systems is particularly challenging to handle from a climate perspective.

As demonstrated in this study, several critical factors and parameters are related to the system level. This has clear policy implications, for one thing since it introduces spatial aspects to landfill mining implementation. Apart from the importance of regionally prevailing energy systems, the accessible WtE plants are to some extent regionally determined, given that new plants will not be built for most landfill mining projects. The importance of highly efficient energy recovery technologies has been recognized in previous studies[13,15,33] and is confirmed by the present analysis. Also when it comes to material recovery, systemic conditions are of high relevance for the climate impact of most landfill mining projects. Here, parameters related to avoided metals production are particularly important, however, difficult to influence on a project basis.

The presented analysis provides policy-relevant knowledge on the general circumstances under which MSW landfills should be prioritized for landfill mining projects from a climate perspective. For instance, for mining old landfills with already well degraded organic, global warming mitigation is not likely to be a main driver due to the limited savings potential associated with relatively low landfill gas generation potentials. However, to develop more specific knowledge for landfill prospecting (i.e., climate impact "landfill cut-off grades" in different project-settings and regions) and project set-ups (i.e., blueprints for improved climate impact given certain types of landfills and system conditions), in-depth assessments of specific groups of archetypical landfill mining scenarios are needed. Furthermore, other environmental impact categories to complement climate impact for a comprehensive assessment of environmental performance, different landfill mining scenarios (e.g., industrial landfills, waste management practices beyond Europe, technology development in the field of thermal treatment and material recovery, etc.) as well as economic indicators should be considered to broaden the scope of future analyses. Such studies can build upon the analytical approaches and statistical methods presented in this work.

The focus of the present analysis has been on choices of practical relevance for developing policies to prioritize landfill mining projects resulting in a reduction of net climate impacts. However, apart from natural variation in the investigated factors, there is also uncertainty about model choices and assumptions (e.g., the model used to determine the landfill gas potential, global warming characterization factors, consideration of biogenic carbon dioxide emissions as climate neutral, etc.). For instance, other characterization methods to account for the global warming impact of greenhouse gas emissions, particularly with respect to biogenic carbon,[36] than GWP_{100} according to the IPPC[34] could be used and may affect the obtained results. Overall, such assumptions and methodological choices may have a significant impact on the model outcomes and should therefore be subject to further research.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01275.

Additional information as noted in the text: detailed description of data sets used for the modeling of factor realizations, linearity check related to the stepwise multilinear regression modeling, graphical analysis of the effect of varying the four least important factors, scenario results in case of choosing a higher methane oxidation rate (40%) in the landfill top cover (PDF)

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■ AUTHOR INFORMATION

Corresponding Author

*E-mail: david.laner@tuwien.ac.at.

Notes

The authors declare no competing financial interest.

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