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Proposal for Feasibility Assessment Model for Landfill Mining and Its Implementation for Energy Generation Scenarios

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Abstract: New approaches to waste management and requirements of a circular economy have changed landfill management. Therefore, the updating on these subjects is required. To benefit from landfill mining, information about composition and properties of disposed waste should be gathered. Decay of landfilled waste over time primarily determines the amount of recyclable and combustible matter as well as the amount of landfill gas formation. In this paper, we propose scenarios for landfill management and we create a conceptual model on their basis. A conceptual model is formulated and theoretical calculations are performed and compared with field research results in order to understand changes in the composition of landfilled waste. Correlations between theoretical and actual results were determined. Correlations of theoretical and actual results for the Torma (EE) and Alytus (LT) landfills were 0.68 and 0.78, respectively. In addition, the changes of refuse-derived fuel resources in Alytus landfill during the previous 10-year period were calculated. Finally, four different landfill closure and aftercare scenarios with respect to energy generation were created, assessed, and compared.

Keywords: municipal solid waste; waste decay rate; landfill gas; landfill aeration; renewable energy; sustainable energy

1. Introduction

Waste management hierarchy indicates an order of preference to manage waste, where prevention, minimization, and recycling are preferred over energy recovery, and landfilling remains the least favored option [1,2]. At least 65% of municipal waste by 2030 should be recycled and landfilling should be reduced to less than 10% [3,4]. While landfilling must be minimized in the future, there is a significant amount of accumulated wastes in existing landfills, which can contribute to the recovery of resources from the anthroposphere. Landfill mining (LFM) would provide a concept for material and energy recovery along the total life cycle of a disposal site. The concept of enhanced landfill mining (ELFM) is supported by multiple international networks [5] and organizations. Research in the LFM area is facing three challenges: technology innovation, the need to address the underlying conditions for implementation, and the need to develop standardized frameworks for evaluating economic and environmental performance from a systems perspective [6,7]. The European Commission aims to further examine the feasibility of proposing a regulatory framework for enhanced LFM to permit the retrieval of secondary raw materials that are present in existing landfills [8]. Mining does not only enable the recovery of valuable materials but also allows for the recovery of land area, taking into account that a large part of the EU's 500,000 historic landfills are situated in a semi-urban environment [4].

Krook and Baas suggested four main aspects of urban and LFM for resource management including metabolic flows, governance and knowledge, business dynamics, and infrastructure and markets [9]. LFM was indicated as a catalytic process by offering complementary sources for feeding the ever-increasing market demand for materials and energy. At the same time, some authorities are inconsistent in LFM, since its ontological complexity makes it difficult to evaluate the feasibility and benefits of LFM [10].

LFM has recently been a subject of scientific investigations, including resource potential [11], technical aspects [12], and economic feasibility [13,14]. Currently, the amount of LFM projects worldwide is comparatively low, but the data on landfill composition and extracted resources has been presented during the past decade [15–17]. Presently, the discussion of the feasibility of LFM and the search for the optimal utilization of resources continues in a conceptual phase by modeling various resource-economy scenarios. Physical investigations of landfills usually serve as forms of input or validation data to the models, such as in the study by Hossain and DeVries [18], who proposed a model associating volatile solid content and landfill depth. Material flows have served as the basis of economic assessment of LFM in Pohlsche Heide landfill (Kreis Minden-Lübbecke, Germany), where a negative economic value of LFM was revealed as opposed to a typical aftercare [19]. However, financial analysis alone cannot demonstrate the economic value of LFM. A resilience model of LFM highlighted the relevance of several aspects of LFM, namely, metabolic flows, governance and knowledge, business dynamics, and infrastructure and markets [9]. Not only were economic and material flow models created for LFM but also life cycle assessment (LCA) models for the evaluation of the environmental impacts of LFM were published [20]. It was noted that LFM feasibility will only improve if separation techniques improve, resources become scarcer, and demand for land development increases [21].

The above presented models tackle economic and technical feasibilities but lack the holistic association between processes in landfills over time and the feasibility of mining from economic, environmental, and technical perspectives. This research study presents an attempt to design a universal model for the assessment of landfill management activities, including: (a) exploitation (including waste disposal, landfill gas extraction, and leachate treatment); (b) mining; (c) maintenance and use in the aftercare period. This includes changes of (a) waste to be disposed, because of an increasing tendency for separate collection and recycling; (b) landfilled waste (degradation of organics); (c) emissions from landfills; (d) economics of extracted materials usage. This model is validated against real data regarding the waste composition in two operating landfills in Lithuania and Estonia. The model contributes to a better understanding of LFM processes and the preparation of excavated materials for recycling and energy recovery.

2. Materials and Methods

2.1. Model Algorithm

The proposed model takes an approach to account for the entire chain of processes related to the landfill exploitation, mining, and maintenance in the aftercare period, as well as following options of resource recovery, such as for the installation of renewable energy sources.

The model includes data from waste generation processes, which depend on the production and consumption in a region as well as social-economic factors. The subsequent treatment options may include treatment in the mechanical biological treatment (MBT) facility, recycling, incineration, and landfilling.

The landfilled waste is then considered as it is undergoing biochemical processes within the landfill, including biogas production (emission of gases to the environment and/or collection by gas extraction system) and leachate formation.

The excavation of landfills is supposed to take place after the end of the aftercare period, taking into account the desirable aeration. Excavated materials are sieved to fine (<20 mm) [22] and coarse (>20 mm) fractions. The fine fraction is backfilled. The coarse fraction is sorted and probably rinsed using treated leachate, thus creating emissions of additionally polluted leachate. Afterwards, the coarse fraction is processed for material recovery whenever possible (e.g., plastic); when impossible, flammables of coarse fraction are diverted to energy generation by incineration. Thus, a processed landfill is considered to be re-cultivated and may serve as a site for the installation of a renewable and sustainable energy (RSE) facility, whose selection depends on local environmental conditions.

A conceptual model relating the above described processes is presented in Figure 1. In this article, we will mainly focus on the processes directly related to energy production (marked by dashes in Figure 1). By mathematically representing the processes involved in the model, the composition of waste in a landfill may be predicted by calculations, assuming waste decay time and waste primary composition.

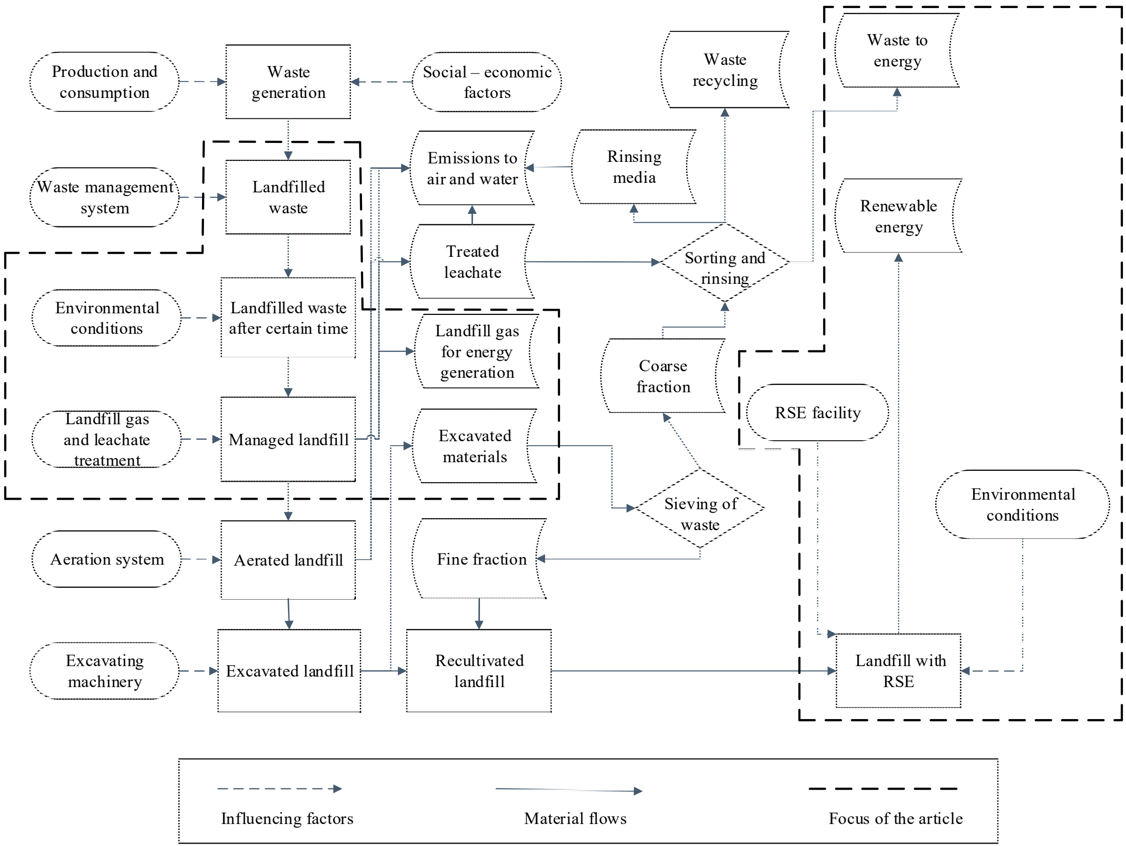

Figure 1. Conceptual assessment model for landfill exploitation, mining, and maintenance in the aftercare period.

2.2. *Transformations of Deposited Waste within the Landfill*

The transformation of waste in the landfill was estimated by assuming the decay of a particular fraction of deposited waste [2]. Such processes may be mathematically fitted into the exponential decay function by calculating the waste decay rate using the first-degree kinetic equation [2]:

$$SW^{t}{}_{Di\ remaining} = SW_{Di} \cdot e^{-kt} \tag{1}$$

where:

$SW^{t}{}_{Di\ remaining}$—amount of dry matter of solid waste fraction i remaining after time t, tons;

SW_{Di}—initial amount of dry matter of solid waste fraction i, tons;

k—the first-degree rate constant for waste fraction i;

t—degradation period in landfill, years.

The values of the decay rate k have been taken from Pipatti et al. [2] and presented in Table S1. The average value of k was used in case the range was presented.

The formation of the fine fraction needs to be estimated next, considering the following composition:

(a) a mineral part of biodegradable fractions after full decay;
(b) particles of non-decayed but particularly crumbled biodegradable waste;
(c) particles of crumbled plastic and weathered glass;
(d) soil added during landfilling process to cover a landfill.

The content of fine fraction was calculated as follows [2]:

$$SW_{DF} = \sum[(SW_{DBi} - SW_{DBi\ t})\cdot\omega] + \sum SW_{DBi\ t\ crumbled} + \sum SW_{DnBi\ crumbled} + m_{soil} + Z; \quad (2)$$

where:

SW_{DF}—formed amount of dry state fine fraction, tons;

SW_{DBi}—initial amount of all dry state biodegradable i fractions, tons;

$SW_{DBi\ t}$—remaining dry state amount of biodegradable i fractions after period t, tons;

ω—ash content for fraction i, %;

$SW_{DBi\ t\ crumbled}$—remaining but crumbled amount of dry state biodegradable i fractions after period t, tons;

$SW_{DnBi\ crumbled\ t}$—crumbled amount of non-biodegradable i fractions after period t, tons;

m_{soil}—soil added to the landfill, tons;

Z—amount of other landfilled material like fine MBT residues and/or incineration ashes, tons.

In this study, weathering of relatively inert materials (e.g., plastic, metals, and glass) was not accounted for. Low quality compost and fly ash was also not deposited, thus the term Z was omitted as well.

2.3. Formation of Landfill Gas

The total formation of methane from landfilled waste was calculated using the Intergovernmental Panel on Climate Change (IPCC) default method [23]:

$$ME = (SW_T \cdot SW_F \cdot MCF \cdot DOC \cdot DOC_F \cdot F \cdot \frac{16}{12} - R) \cdot (1 - OX) \quad (3)$$

where:

ME—methane formation, tons/year;

SW_T—total municipal solid waste (MSW) generated, tons/year;

SW_F—fraction of MSW disposed to solid waste disposal sites;

MCF—methane correction factor (fraction);

DOC—degradable organic carbon (fraction) (kg C/kg SW);

DOC_F—fraction DOC dissimilated;

F—fraction of CH_4 in landfill gas (IPCC default is 0.5);

16/12—conversion of C to CH_4;

R—collected CH_4, tons/year;

OX—oxidation factor (fraction—IPCC default is 0).

Default DOC values for major waste streams employed in this study are presented in Table S2.

The generation of methane was calculated for each fraction individually. The total energy from collected methane was then calculated by summing up methane formation from all individual fractions and multiplying by calorific value of biogas, whereas gas collection efficiency was suggested by the US EPA (United States Environmental Protection Agency) [24]:

$$EM = \Sigma ME_i \cdot 16 \cdot 0.75 \quad (4)$$

where:

EM—energy from methane, MJ;
ΣMEi—sum of methane formed from all biodegradable fractions of waste, Nm^3;
16—biogas lower calorific value, MJ/Nm^3;
0.75—collection efficiency of landfill gas [24].

By volume, landfill gas typically contains 45% to 60% methane [25].

2.4. Energy Potential of Combustible Fractions of Excavated Waste

Energy potential of excavated waste depends on the moisture content and chemical composition. In the presented model, the energy potential of waste fractions was calculated using Dulong's correlation [26]. Firstly, a higher heating value was calculated for dry weight of the fraction [26]:

$$HHV_i = 338 \cdot C + 1442 \cdot (H - O/8) + 94 \cdot S \quad (5)$$

where:

HHV_i—higher heating value of i fraction, kJ/kg;
C, H, O, S—content of chemical elements in fraction i, %.

The chemical composition of waste fractions was calculated using elemental composition [27].

The lower heating value of dry waste was calculated by subtracting the amount of energy needed to evaporate water from a fraction [28]:

$$LHV_i = HHV_i - 24.41 \cdot \frac{18.01}{2.02} \cdot MC_i \quad (6)$$

where:

LHV_i—lower heating value of i fraction, kJ/kg;
MC_i—moisture content of i fraction.

The lower heating value of the wet waste fraction i was then calculated as follows [28]:

$$LHV_{iww} = LHV_i \cdot \frac{(100 - MC_i)}{100} - 24.41 \cdot \frac{(100 - MC_i)}{100} \quad (7)$$

where LHV_{iww} is the lower heating value of wet waste fraction, kJ/kg.

The total energy potential of landfilled waste was calculated as follows [28]:

$$E_{SW} = (\Sigma LHV_{iww} \cdot SW_{\mathrm{i}}) \cdot \eta \quad (8)$$

where η is energy efficiency (for power and heat generation) during the incineration of excavated materials, estimated by [28] as 85% for heat generation, 35% for electricity generation.

2.5. The Use of Excavated Landfill Area for Renewable Energy Generation

The reclaimed landfill area after the excavation may be further utilized for the installations of renewable energy facilities.

The energy density of wind power generators was assumed to be 0.95 W/m^2, as suggested by Energyadvocate [29].

The electricity generated from a photovoltaic system was calculated based on the following relationship [30]:

$$E_{solar} = A \cdot r \cdot H \cdot PR \tag{9}$$

where:

E_{solar}—annual energy from photovoltaic installations, GJ;
A—total solar panel area, m^2;
r—efficiency factor given by ratio (0.11–0.13);
H—annual average solar radiation on tilted panels (shadings not included), kWh/m^2;
PR—performance ratio, coefficient for losses (0.5–0.9).

The annual energy from energy crops was estimated using data from Reilly et al. [31]. Total energy from energy crops from a landfill can be calculated as follows:

$$E_{crops} = A_{crops} \cdot 0.02 \tag{10}$$

where:

E_{crops}—annual energy from energy crops, GJ;
A_{crops}—area of landfill, sown with crops, m^2;
GJ/m^2/year—energy potential of crops.

2.6. Investigated Landfills

Data from Alytus landfill in Lithuania and Torma landfill in Estonia were used for validation of modeling scenarios. Alytus regional landfill was opened in 2007. The total area of the landfill is 26.2 ha. Approx. 600,000 tons of waste is currently deposited in the landfill.

Torma landfill was opened in 2001 and is located in Jõgeva County. The landfill covers an area of 6.2 ha. The landfill contains three cells with different ages of MSW [32].

2.7. Morphological Composition and Quantity of Waste in Landfill

2.7.1. Experimental Determination of Waste Composition

The morphological composition of landfills was investigated experimentally by the method of drilling (Alytus) or excavation (Torma). Investigations were made according to the Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste (D 5231-92). In Alytus, three drillings were conducted with a 15-cm drill in specified parts of the first section (which has been operating from year 2007 onwards—later we will talk specifically about the first section) and waste samples were drawn every meter between 1 and 10 m in depth [33]. In total, 285 kg was excavated. The waste was sorted into four size fractions (>80 mm, 80–40 mm, 40–20 mm, and <20 mm). The waste was classified into paper and cardboard, glass, textiles, soft plastics, hard plastics, medical and other non-combustible, electronics, and fine fraction. The results of the investigation are presented in Figure 2 (WEEE—Waste Electrical and Electronic Equipment).

In Torma, a bucket excavator excavated a test pit which was about 4 m deep, and samples were taken from each meter to represent four layers of waste. Samples weighing 1735 kg were drawn from the four layers. Each sample was manually sorted on a conveyor belt to the same fractions like in Alytus. The quantity of the fine fraction was determined by manually sieving the residue to <20 mm [32].

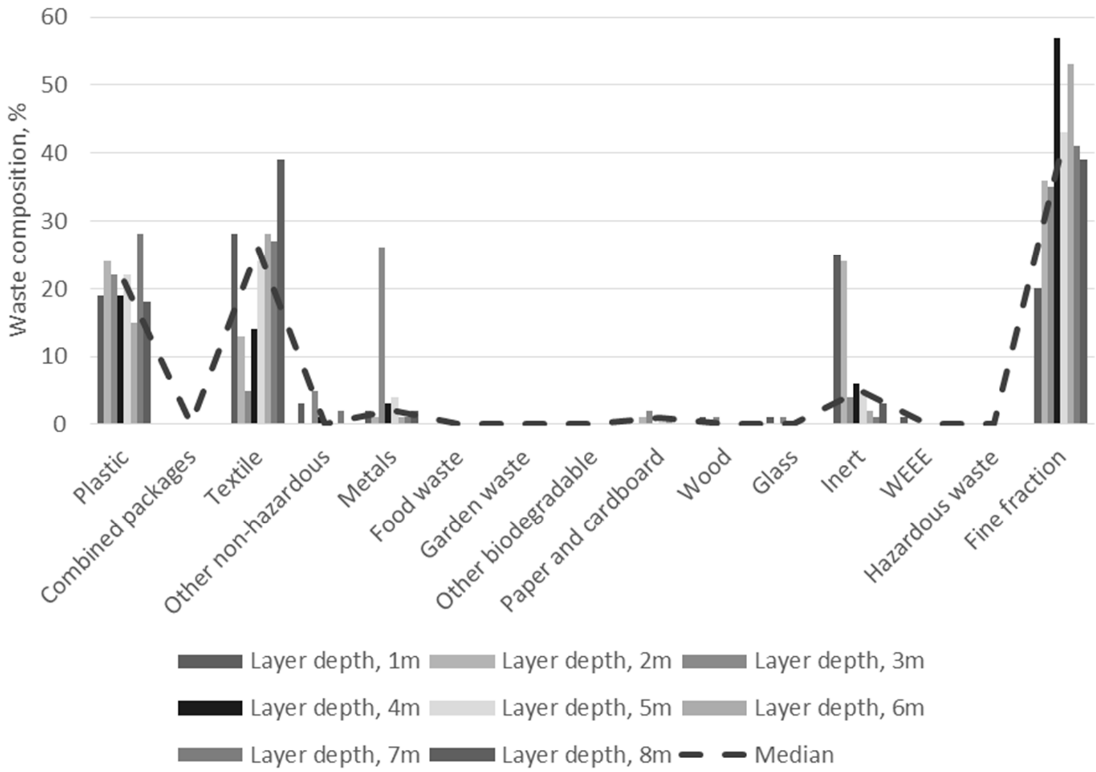

Figure 2. Average composition of waste in Alytus landfill (%).

2.7.2. Mathematical Prediction of Landfill Composition

Alternatively, the landfill composition was modelled using multiple regression technique, taking advantage of the established relationship between landfilled waste and the economic activity of the surrounding region. The regression model, which mathematically describes the connection between economic activity and the generation of MSW, was formulated by Christiansen and Fischer [34] and was further implemented in the Life Cycle Assessment Tool for the Development of Integrated Waste Management (LCA-IWM) assessment tool [35]. This model can be used to assess the amount of fractional composition and the total amount of municipal solid waste regardless of the degree of separate collection. This model is used for the morphological estimation of waste when there is no statistical data [35]:

$$P_i = a \cdot SW_i^{\,2} + b \cdot SW_i + c \tag{11}$$

where:

P_i—share of i fraction in common generated waste flow, kg per capita;
a, b, and c—coefficients for different waste fractions (Table S3).

Separate collection both in Lithuania and in Estonia was started in 2004. Therefore, when common generated waste amount and composition from recent years is determined, it is necessary to deduct the shares of waste that are recycled, treated in a MBT facility, and incinerated:

$$SW_{landfilled} = \sum SW_i - \sum SW_{recycled} - \sum SW_{MBT} + \sum SW_{MBT-B} - \sum SW_{incinerated} + SW_{ashes}; \tag{12}$$

where:

$SW_{landfilled}$—final landfilled waste amount, tons;
ΣSW_i—sum of generated waste fraction amounts, tons;
$\Sigma SW_{recycled}$—sum of separately collected and recycled waste fraction amounts, tons;

ΣSW_{MBT}—sum of waste fraction amounts passing to mechanical-biological treatment, tons;
$\Sigma SW_{MBT\text{-}B}$—sum of waste fraction amounts remaining after mechanical-biological treatment and stabilization and returning to the landfill, tons;
$\Sigma SW_{incinerated}$—sum of incinerated waste fractions, tons;
ΣSW_{ashes}—ashes returning to the landfill after incineration, tons.

This formula is especially useful for the calculation of recent landfilled waste flow. In the current study, MBT and ashes (incineration residues) were not included, because it was not yet implemented in both countries during the disposal period.

The amount of soil used to cover waste volume is calculated according to the following equation [36]:

$$m_{soil} = 0.22 \cdot SW_{landfilled} \tag{13}$$

where:

m_{soil}—amount of soil used to cover waste volume, tons;
$SW_{landfilled}$—amount of landfilled solid waste, tons.

Landfill cover density is in a range of 1.6–2.6 t/m^3. After the evaluation of amounts of landfilled waste, their decayed share must be estimated.

Changes in GDP (Gross domestic product) and separate collection rates of waste in the Alytus region, both of which were used in calculations, are presented in (Figure 3) [37,38].

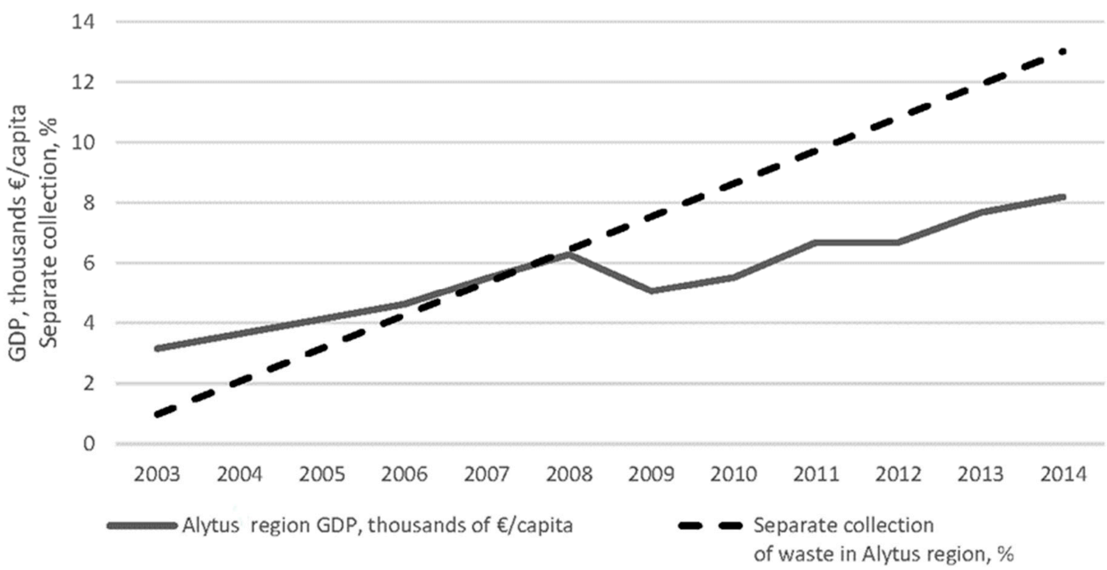

Figure 3. Changes in the GDP (in thousands of €/capita) of the Alytus region and separate collection of waste in the Alytus region.

The composition of waste disposed in the Alytus landfill was calculated by using the median of one-year results of surveys of all waste collected in the Alytus waste management region. Investigations in the Alytus landfill and the Torma landfill in Estonia are described above. The theoretical calculation of waste composition in the landfill was made using data from waste disposal in the Alytus landfill waste composition, (1) formula, and k values from Table S1. Calculation results are presented in Figure 4.

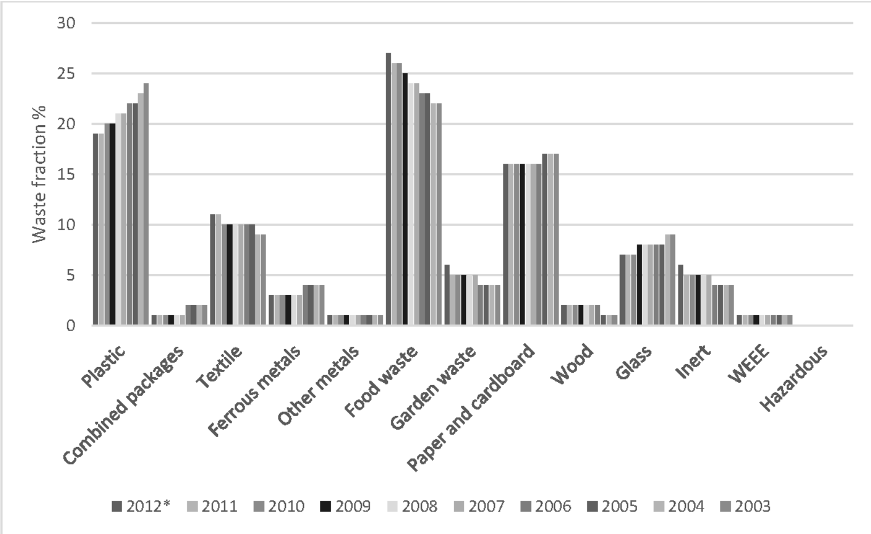

Figure 4. Composition of waste disposed of in the Alytus landfill during a 10-year period (2003–2012).

3. Results and Discussion

3.1. Model Validation

As evident from Figure 4, different fractions were changing in different ways. The percentage of non-degradable fractions (plastic, combined, metals, glass, inert, WEEE (Waste Electrical and Electronic Equipment), hazardous waste, and fine fraction) increased over time, while the others (partially degradable textile, food and garden waste, paper and cardboard, wood, and other biodegradable) were decreasing. This was due to biodegradation of the latter fractions, with part of the organic matter leaving the landfill as gases and leachate. The amount of completely degraded organic matter is accounted for in the fine fraction, the percentage of which also increased at the expense of cover material. A comparison of the calculated waste composition in the Alytus landfill and the actual waste composition in the Torma landfill is presented in Figure 5.

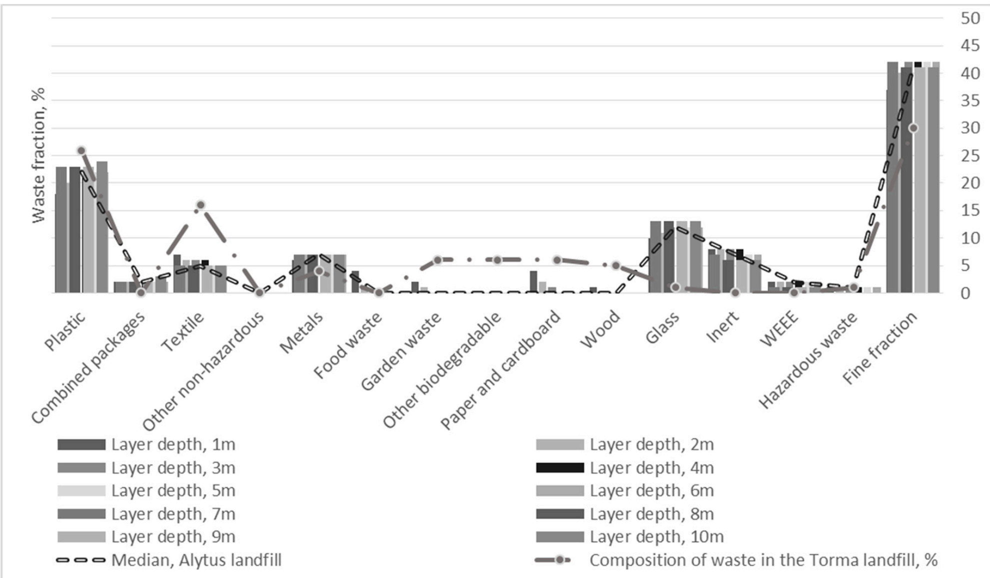

Figure 5. Calculated waste composition in the Alytus landfill (Lithuania) and actual waste composition in the Torma landfill (Estonia), in %.

Field research and theoretical calculation results for landfill composition have been compared. The waste, which was excavated from the Torma landfill, was between 3 and 5 years old. Correlations between results are presented in Figure 6. Both correlations between calculated and actual composition in Alytus and Torma landfills are strong. This can be explained by the tendency for the composition of waste in landfills in countries with similar social-economic situations (in our case Estonia and Lithuania) usually being similar.

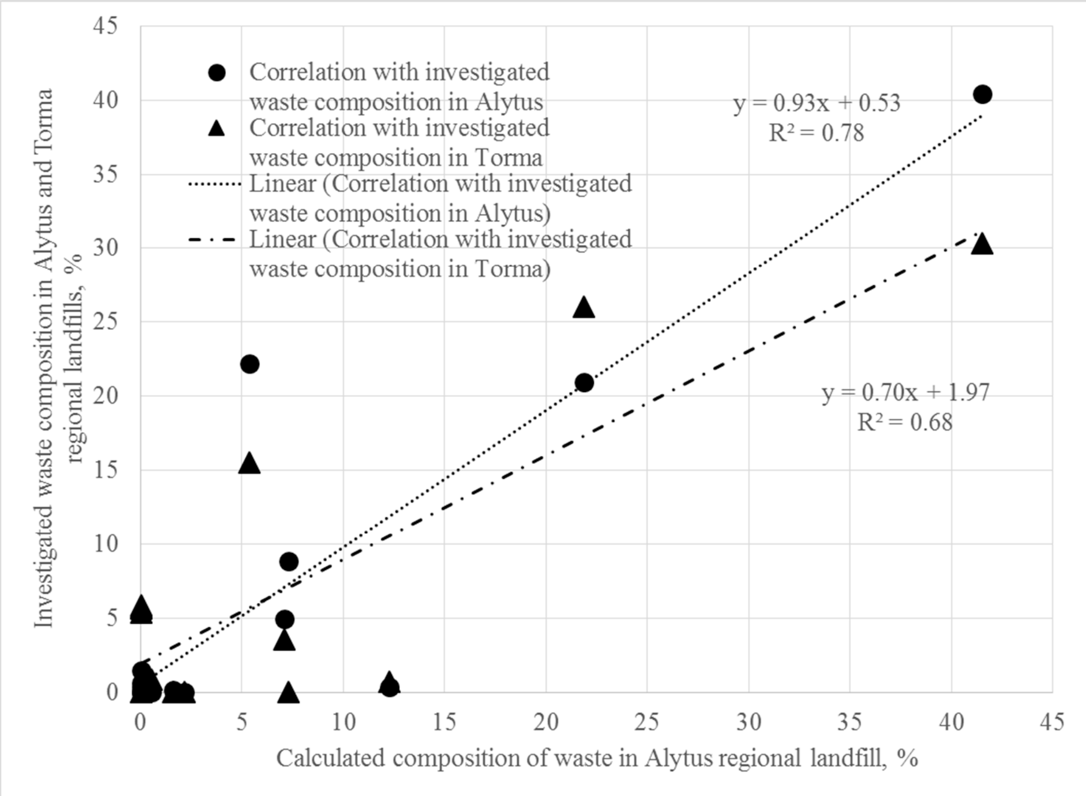

Figure 6. Comparison of correlations between median of calculated waste composition in the Alytus landfill and medians of waste compositions excavated from the Torma landfill and the Alytus landfill.

3.2. Landfill Management Scenarios

Four scenarios for extracting the maximum amount of energy from the Alytus landfill were compared. Possible scenarios are illustrated in Figure 7. Initial calculation parameters for Figure 7 are selected as follows:

(a) In the first scenario, energy from landfill gas is recovered for 20 years, afterwards the landfill is excavated, then solar modules and wind turbines are installed and renewable energy is produced for 30 years;
(b) The second scenario consists of landfill gas collection and energy production, followed by LFM, and then energetic plants are planted, grown, and exploited for 30 years;
(c) The third scenario does not include LFM, only landfill gas collection for 20 years, followed by the installation of solar modules and wind turbines and the generation of renewable energy for 30 years;
(d) The fourth scenario includes LFM, followed by the growing of energetic crops for 30 years. Since for better efficiency we are going to produce both heat and electricity, for total energy calculations we can use typical combined heat and power (CHP) efficiency of 75% [39].

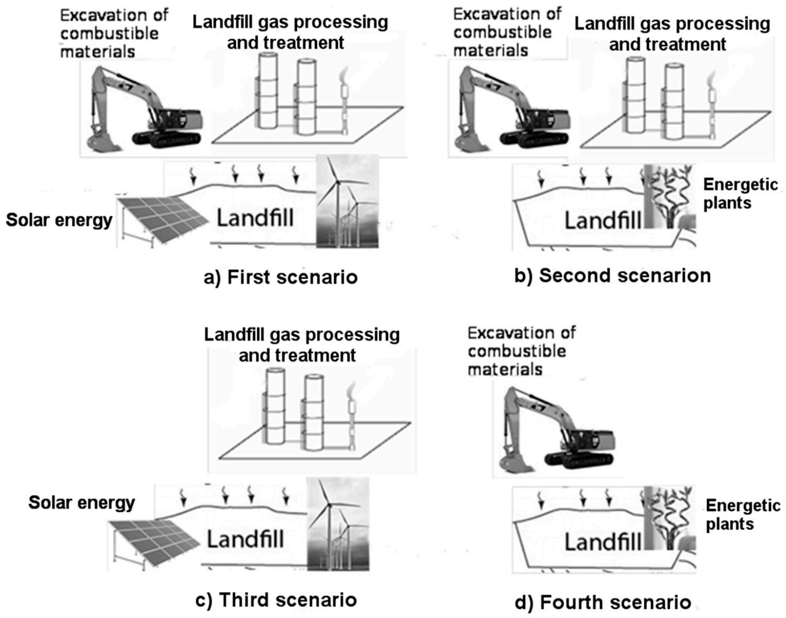

Figure 7. Schematic illustration of the four scenarios: (**a**) landfill gas + excavated combustibles + wind/solar; (**b**) landfill gas + excavated combustibles + energetic crops; (**c**) landfill gas + wind/solar; (**d**) excavated combustibles + energetic plants.

The results of the calculations from the different scenarios are presented in Figure 8. It is clear that the largest total amount of energy comes from the incineration of waste, which is obtained from LFM, followed by energy from solar panels, then in descending order by energy from wind turbines, energetic crops, and methane extraction. All results are true only with current input parameters (e.g., duration of energy generation by wind turbines).

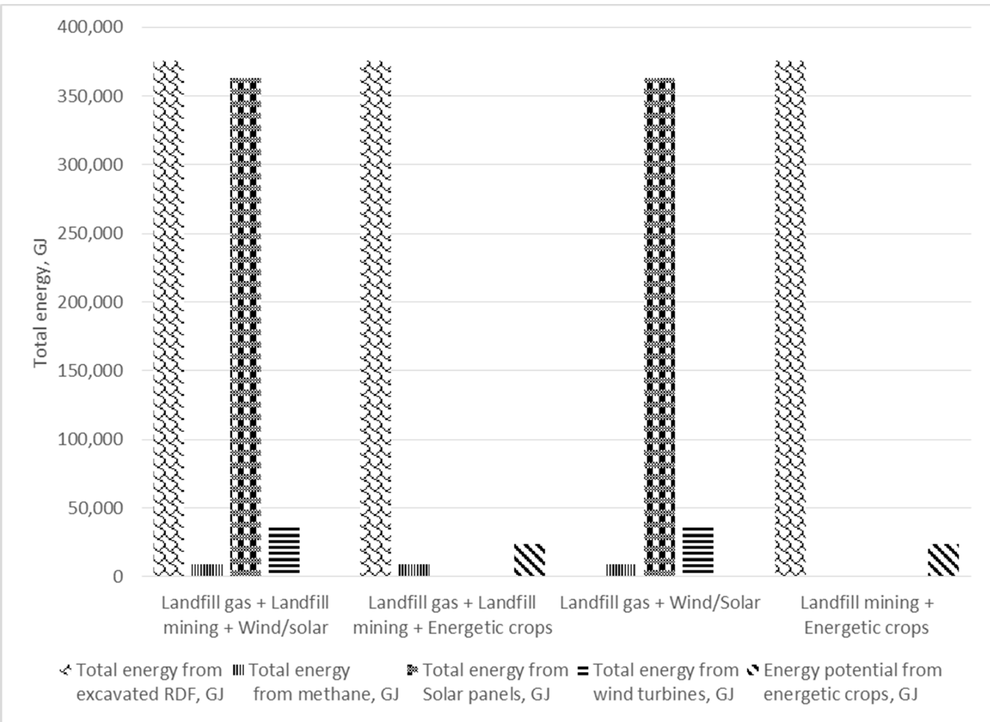

Figure 8. Comparison of several scenarios of closure of the Alytus landfill.

4. Conclusions

The research described in this paper mainly focuses on the modelling of changes in the composition of landfilled municipal solid waste, with the aim of proposing scenarios for future landfill management. Actual waste composition in two landfills in Estonia and Lithuania were studied, and the alteration of waste content and energetic value over time were calculated. The model was validated with field experiments. A new feasibility model for energy generation during future landfill management was proposed. It is focused mainly on waste decay with the corresponding changes of combustible fractions and landfill gas generation during landfill exploitation and aftercare periods and energy generation feasibilities in the aftercare period. Further development of the model must concern the mechanical treatment of excavated waste and energy generation during incineration of obtained refuse-derived fuel (RDF). Model validation showed a strong correlation between calculated and investigated results, with the correlation with waste excavated from the Torma (Estonia) landfill waste being 0.68 and the correlation with waste excavated from the Alytus (Lithuania) landfill waste being 0.78. Calculations of energy potential showed similar results with other authors [11]. For a complex view of LFM, not only does waste decay play an important role, but also the overall cycle of landfill management, including its aftercare use for energy generation—that is why the evaluation of different energy recovery scenarios during the landfill closure cycle is also relevant. As evident from the comparison of scenarios, the largest amount of energy during the aftercare period can be obtained from the incineration of excavated waste, followed by energy from solar panels, wind turbines, and energetic crops. Landfill gas energetic potential was the smallest. Therefore, after extraction of landfill gas for energy uses it is advisable to excavate combustible materials for incineration and establish solar panels in the area afterwards. The proposed model helps with the goal of moving toward the establishment of a circular economy by improving waste recycling and the conversion of waste into resources.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/8/2882/s1, Table S1: Waste decay rate (*k*) values (Pipatti et al., 2006), Table S2: Default DOC values for major waste streams (Froiland and Pipatti, 2006), Table S3: Coefficients for calculation of municipal solid composition (den Boer et al., 2007).

Author Contributions: A.B. and G.D. designed the model and the computational framework and analysed the data. G.D. and M.K. helped supervise the project. A.B. took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

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Conflicts of Interest: We have no conflict of interest to declare.

Abbreviations

LFM/ELFM	Landfill Mining/Enhanced Landfill Mining
RDF	Refuse-Derived Fuel
MSW	Municipal Solid Waste
MBT	Mechanical Biological Treatment
RSE	Renewable and Sustainable Energy
CHP	Combined Heat and Power
LCA-IWM	Life Cycle Assessment Tool for the Development of Integrated Waste Management
IPCC	Intergovernmental Panel on Climate Change

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