energies

MDPI

Article

Energy Production from Landfill Gas: Short-Term Management

Nuno Soares Domingues

Engineering Department, Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, Rua Conselheiro Emidio Navarro, 1, 1959-007 Lisbon, Portugal; nuno.domingues@isel.pt or nndomingues@gmail.com

Abstract: An increasing lack of raw materials, resource depletion, environmental impacts and other concerns have changed the way the population faces garbage disposal and municipalities implement waste management strategies. The aggravated global rise in municipal solid waste (MSW) generation has led to a new stage in full development, with objectives and targets set by the European Union regarding reducing the production of MSW. The targets also include the increasing selective collection, reuse, recycling and recovery (organic and energetic) of the waste produced. At the same time, the European Union has also set caps for the greenhouse gas emissions and for increasing the use of alternative renewable energy sources. In this context, one of the sources of renewable energy that is beginning to be used to produce electricity in our country is biogas. Finally, AD promotes the development of a circular economy. The present study introduces the formalism for a computer application that simulates the technical–economic behaviour of the short-term management of biogas for the conversion of electricity, and the mathematical model is formulated as a mathematical programming problem with constraints. A simulation for a case study of short-term management is given using the real landfill data available. The case study proves the ability of the LandGEM, despite some authors' support that the Tabasaran–Rettenberger model provided a more reliable estimate, especially when compared to actual landfill data. The present paper is a contribution to the optimisation of the management of electricity from the use of biogas, namely the second phase of the Strategic Plan for Urban Waste. In addition to complying with the legislation in force, the use of biogas to produce electricity is an added value for the concessionaires of waste treatment and final destination units, as this alternative energy source can provide not only self-sufficiency in electricity for these units but also the export of surplus energy to the National Electricity Grid, thus contributing to the self-sustaining management and energy flexibility that is intended for these infrastructures.

Keywords: biogas; landfill gas; waste to energy; municipal solid waste; renewable energy; anaerobic digestion; energy management

Academic Editor: Albert Ratner

Received: 27 January 2025
Revised: 14 March 2025
Accepted: 31 March 2025
Published: 11 April 2025

Citation: Domingues, N.S. Energy Production from Landfill Gas: Short-Term Management. *Energies* **2025**, *18*, 1974. https://doi.org/10.3390/en18081974

1. Introduction

Biogas is a mixture of methane (CH_4) and carbon dioxide (CO_2), being produced by anaerobic digestion of organic matter (sewage, manure, organic/agricultural waste, etc.). Using biogas that comes from the anaerobic decomposition of municipal solid waste (MSW) deposited in landfills achieves two objectives: it reduces the emission of methane into the atmosphere through the capture and burning of biogas, as required by Decree Law No. 152/2002 of 23 May and subsequent laws, contributing to the energy recovery of waste, and increases the electricity system's flexibility. Thereby, energy use to produce electricity has energetic, economic and environmental benefits.

The top objective of policies is to guarantee an appropriate purpose for waste, thereby reducing consequences to human wellbeing and to the environment by ensuring that waste management is carried out using appropriated processes or methods. In this way, it is essential that waste is properly separated and classified at source [1], so that its destination is the most appropriate and the least harmful to both parties, promoting a circular economy for the preservation of resources and promotion of sustainable economic growth. Decentralised composting, such as domestic and community, is a biologic treatment for biowaste that can be applied in urban areas and follows a circular economy concept. The process of using energy starts with the collection of waste itself, which is then decomposed and followed by transport to the places of consumption, where direct combustion is carried out by replacing the use of fossil fuels. Industries in the forestry sector have been using biomass to produce thermal and electrical energy for about 30 years. The energy ratio of 1 ton of wood is equivalent to 0.359 toe (ton of oil equivalent) for conifers or 0.331 toe for broadleaves. The calorific value of the biomass produced annually in Portugal is about two million toes [2].

MSW management around the world is at different stages, from almost absent to strong commitment. Being in action in the EU, waste management practices vary between Member States. The EU wants to promote waste prevention and the reuse of products as much as possible. If this is not possible, preference is given to recycling (including composting), followed by using waste for energy production. The most harmful option for the environment and people's health is simply the disposal of waste, which is, for example, landfilled, although this is also one of the cheapest possibilities. In October 2022, Parliament approved a revision of the rules on persistent organic pollutants (POPs) to reduce the amount of harmful chemicals in waste and production processes. The new rules introduced stricter limits, banned certain chemicals and kept pollutants separate from recycling [3]. In February 2021, Parliament had already adopted a resolution on the new circular economy action plan calling for additional measures to achieve a carbon-neutral, sustainable, toxic-free and fully circular economy by 2050, including stricter recycling rules and mandatory targets for the use and consumption of materials by 2030 [4–6].

In Portugal, in the last decade, there has been a major change in the urban MSW policy, with about 341 existing landfills being closed and recovered, and 37 landfills built in their place. At the same time, the management of MSW, which, until 1994, was the exclusive responsibility of the local authorities, has been open to public and private concessionaires, contributing to the improvement of the services provided to the users of the systems and to the strengthening of the investment capacity. In July 2003, the Ministry of Cities, Spatial Planning and Environment presented the "National Strategy for the Reduction of Biodegradable Urban Waste to Landfills", which systematised the projections of waste generation and outlined the guidelines for balanced management, with an emphasis on the objectives of recycling and recovery using the best available technologies. Public–private partnerships in areas such as biodegradable waste are also being put forward. The Strategic Plan for Urban Waste (PERSU—Plano Estratégico para os Resíduos Urbanos) (approved by the Council of Ministers, Resolution No. 30/2023, of 24 March) already eradicated garbage dumps and provided the country with basic and essential infrastructures in terms of MSW management. In progress is the study focusing on optimising the management of the systems already built through the evaluation and analysis of their performance.

2. Biogas Production Technologies

Biogas can be obtained from two main technologies: anaerobic digestion (biochemical conversion), followed by cleaning and conditioning of the biogas, and biomass gasification (thermochemical conversion). As a technology for the organic recovery of biomass and biodegradable waste under the General Waste Management Regime (RGGR), anaerobic digestion is more suitable for the degradation of liquid organic effluents, while gasification tends to apply more to lignocellulosic materials (e.g., some agro-industrial residues and forest residues) with low moisture content that are not subject to rapid biological decomposition. Currently, anaerobic digestion is the most mature technology to be at the base of the biogas production value chain in the short term, and there are already several units in operation, both in Portugal and in Europe. As a biotechnology for the treatment and organic recovery of effluents and waste, anaerobic digestion allows for the reuse of a wide variety of biodegradable organic substrates, mainly from agro-industries, agriculture, food industry, urban solid waste management and wastewater. This process is based on the biological conversion of organic matter through the coordinated action of microorganisms (Bacteria and Archaea) in the absence of oxygen and is based on four sequential steps, including hydrolysis, acidogenesis, acetogenesis and methanogenesis. In the end, the result is the formation of biogas, a combustible gas with well-established applications in the production of electrical and/or thermal energy by direct burning. In addition, the process also results in a digestate that can be used directly in agricultural recovery as an organic corrective and that has commercial value as a biofertiliser after the appropriate treatments.

From the different available solutions in managing MSW, anaerobic digestion (AD) systems, a natural biological process to convert organic waste into biogas, show to be better and are currently implemented worldwide. Thereby, AD application is primarily the production of renewable energy and sustainable waste reduction solutions [7], although it has been primarily driven by satisfying the energy needs concerning climate change and the need to increase the use of non-fossil fuel [8]. Considered green renewable, the common composition of biogas consists mainly of methane (CH_4) and lower parts of carbon dioxide (CO_2) and hydrogen sulphide (H_2S).

Many benefits result from AD for waste reduction. Using AD can recover 60% more energy than direct combustion (such as with incineration) [9]. Also, the effluent from AD produces rich fertiliser, which can be used for replenishing nutrients in the soil. In addition, the methane produced and collected from AD can reduce greenhouse gas emissions, as it is captured and used to generate green energy [9].

Biogas can also go through a purification process to make its composition as similar as possible to that of fossil natural gas, then becoming biomethane. Biomethane is biogas followed by methanation of the carbon monoxide present in the syngas: two processes that are largely complementary. Biomethane can also be produced through power-to-methane using biogenic carbon dioxide and green hydrogen, which is one of the most promising future avenues for large-scale biomethane production. Biomethane is used as a biofuel in the form of a CNG or LNG substitute, called bio-CNG or bio-LNG. Biomethane in transport is a high performer in terms of the reduction of GHG emissions, if we consider the full carbon footprint of the vehicles (Well to Wheel) [10].

A classic landfill is a place where waste is placed in open air or is buried in the ground in large amounts. These landfills have the potential to cause several issues. Infrastructure disruption, such as damage to access roads by heavy vehicles, may occur. The pollution of local roads and watercourses from wheels on vehicles when they leave the landfill can be significant and can be mitigated by wheel washing systems. Pollution of the local environment, such as the contamination of groundwater or aquifers or soil contamination, may occur as well. A modern landfill is a waste disposal structure that must have, among others, a collection and treatment system that prevents the pollution of groundwater (providing a correct route for harmful products) and a system for capturing and burning biogas to prevent it from polluting the atmosphere.

3. Methodology

Ref. [11] describes the landfill used for the calculus and data analyses for the case study of the present paper. Figure 1 illustrates the whole system of the landfill, starting from the MSW reception till the conversion to gas and electricity. The liquid wastes are transported to municipal wastewater treatment plants nearby. The fertiliser from sludge is sold on-site.

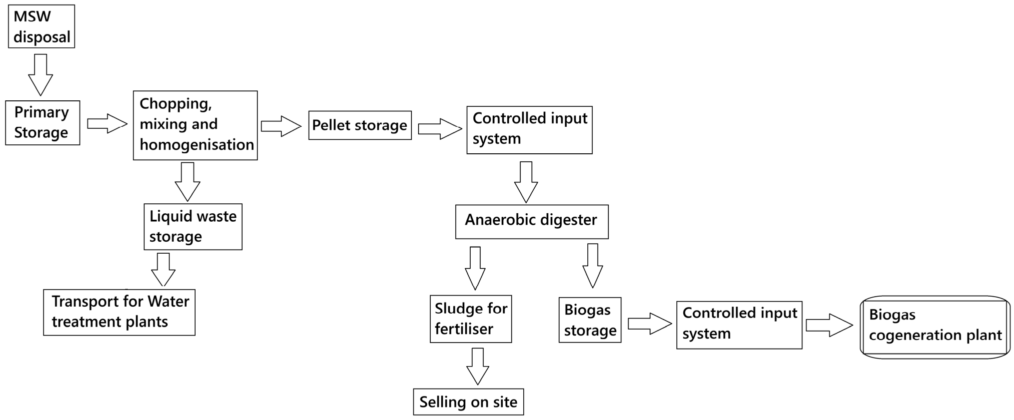

Figure 1. Landfill diagram.

The construction of the sanitary landfill included the most advanced environmental protection and public health technologies, namely:

- Bottom and slope waterproofing;
- Drainage systems and leachate treatment (resulting from the decomposition of organic waste);
- Systems for capturing gases resulting from the decomposition of organic matter.

The operation of the landfill obeys strict procedures and operations carried out daily. At the end of each day, the landfill is completely regularised, covered with earth and with no waste in sight, without translating any risks or inconveniences to the environment. After a cell is fully filled, it will be conveniently sealed. The sealing of each cell allows for a natural recovery, enabling the creation of green spaces and their landscape integration into the surrounding environment.

The biogas burning unit and the adaptation of the landfill cost around EUR 1.5 million in a project that was completed about a year ago. In order to prevent its saturation, a siphon connection was created to a reservoir from which the accumulated condensate is collected. A sweeping line was also installed to clean condensate that may exist in the connection branches. When the closing level is reached, the wells are headed and connected to the perimeter pipeline. To reduce the visual impact, the slopes are sealed with a layer of clay soil regularisation and with a 2.0 mm HDPE geomembrane. The unit is located next to the ETAR-Norte, where the Biogas Production Unit and the Upgrading and Liquefaction Unit will be installed, which will treat, annually, 40,000 tons of poultry waste, 40,000 tons of pig effluents and 20,000 tons of other waste, with an energy production capacity of 40–50 GWh/year.

At the landfill, the production of biogas was qualitatively monitored throughout the degassing process using a biogas analyser and a thermal anemometer. The biogas analyser measured the content of methane (CH_4), oxygen (0), carbon dioxide (CO_2) and, in ppm, carbon monoxide (CO) and hydrogen sulphide (H_2S). Based on the difference, the "balance gas" is determined, mostly nitrogen (N_2). To verify the biogas production potential of the waste deposited in the Leiria landfill and the feasibility of its energy use, there are several theoretical models that allow for the estimation of the production level (see Table 1). The biogas production estimate was obtained using [11] and used to estimate the emission rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds and individual air pollutants from municipal solid waste (MSW) landfills [12]. The simulation was based on first-order kinetics. This model assumes that biogas production is more intense in the period immediately after the waste is landfilled and that production decreases thereafter [13,14].

LFG generation is highly dependent on waste moisture content, increasing because it contributes to an increased rate of waste decay. However, the total amount of LFG generated over time ("ultimate yield") may not increase with increases in the moisture content above a minimum threshold needed to support microorganisms that generate LFG [13]. Moisture conditions can vary widely on-site or due to liquid recirculation. The average annual deposition is typically used as a surrogate for moisture due to the difficulty of measuring moisture within a waste mass [14,15].

For more profitable management of this energy source, it is necessary to consider the variation in rates to achieve more convenient production, although this requires some retention capacity of biogas. However, as most renewable energy plants, it has a small storage capacity, increasing the uncertainty of the amount of fuel available. In this paper, the results of a model to support the short-term management of this energy source are presented, modelling the technical–economic behaviour and constraints via a problem of programming nonlinear mathematics with constraints. This study is essential, as it carries out risk analyses from a commercial point of view, not forgetting that the infrastructures properly framed in the region serve and have an effective connection to their user's decisiveness.

Sustainability in the food waste treatment industry depends on the management of biogas. To address this issue, Ref. [16] proposes a complete evaluation framework, centred on energy, emissions and economic analysis, based on different MSWs. Diverse waste management strategies are characterised by different economic and environmental performances, which makes the modelling and assessment of diverse strategies difficult [7]. Therefore, the integration of different assessment methods can provide holistic information on these performances by complementing each other's advantages [17].

The equation of the model and the variables involved in it are as follows:

$$Q_{CH4} = L_O.R.(e^{-Kc} - e^{-Kt}) \quad (1)$$

where the following hold true:

Q_{CH4} = methane produced in the calculation year (m^3/year);
L_O = methane production potential (m^3/ton of waste);
R = average annual deposition over the working life of the landfill (tonlan);
K = methane production rate (year-I);
c = time since landfill closure (year);
t = time since landfill start-up (year).

The values used for the above variables were those recommended by the EPA for landfill emissions without specific data: Lo = 170 m^3/Mg of refuse and K = 0.05 L/year.

The initial size of the waste stream on the landfill has been determined to be approximately 350 tons per day, based on 260 days (5 working days per week) of deposition in a year. This would, therefore, represent the initial rate of deposition (IRD) for determining the size classification of the site. To determine the maximum rate of deposition (MRD) at the end of the site life, a conservative growth rate of 3% per annum was used for calculating the landfill airspace required for 20 years of waste disposal.

The converter system used to use this energy source for energy production consists of an alternator coupled to an internal combustion engine powered by biogas.

The determination of landfill gas (LFG) generation and the estimation of methane emission are essential for the planning and design of LFG. For the projection of LFG generation over time from a mass of landfilled waste, one can use models with a low cost and relatively rapid result advantages, as compared to field measurement by the use of test wells [18–20].

Several mathematical models can be used to calculate the amount of landfill gas generated by solid waste landfills. Table 1 resumes the main models for determining methane emissions and indicates some studies that provide a practical example based on a calculation.

Table 1. Different models for determining methane emissions.

Method	Model	Case Studies
Residual Waste: Tabasaran and Rettenberger	First-order kinetics	[21]
Tier 2 IPCC	First-order kinetics (Tier 2)	[22]
LandGem (USEPA)	First-order kinetics	[23]
GasSimLite	First-order kinetics	[24]
Aderne	First-order kinetics	[25]
IPCC Tier 1 and Tier 2	First-order kinetics	[26]

By comparing the ability of the models to estimate the CH_4 emissions from a landfill site, Refs. [21–26] show that the Tabasaran–Rettenberger model [27] provided a more reliable estimate, especially when compared to actual landfill data. This finding emphasises the importance of selecting models that account for the waste composition and environmental conditions of the landfill site. Refs. [21–26] suggest that the Tabasaran–Rettenberger model [27] could be a valuable tool for predicting the gas production potential of landfill sites in areas with similar waste characteristics.

The amount of solid waste generated in waste management varies depending on the population, settlement characteristics, season, climate and the consumption habits of people.

4. Short-Term Management

Biogas is a mixture of CH_4 (40 to 60%), CO_2 (20 to 40%) and N_2 (2 to 20%), and there may also be some H_2S (4 to 100 ppm). The production of biogas varies over the years as waste decomposes. CH_4 is a gas that is about twenty-one times more harmful than CO_2 from the point of view of the greenhouse effect [23,26–29]. The management of energy use of biogas for conversion to electricity leads to economic valorisation from the sale of electricity [30], with prices better than those of conventional sources, or possibly in the future, to the value of green certificates, which are already in operation in some European countries. Moreover, because CH_4 is more harmful than CO_2 from the point of view of the greenhouse effect, its use as a fuel represents an environmental benefit.

In this communication, a computer application for the management of this energy source in the short term is described, considering the price variation and the CH_4 emission estimated using the history and/or particularly in the design phase of the USEPA LandGEM model [31]. The behaviour of the technical–economic mechanism game is modelled by a nonlinear mathematical programming problem with constraints, using the notations presented below:

J—set of indices of restrictions by stadium;

N—set of indices n of constraints over the time horizon;
K—set of indices k of the stages of the time horizon;
a_{jk}—a set of units that must satisfy the constraint j at the stage k;
b_n—a set of units that must satisfy constraint n over the time horizon;
c_{ik}—biogas consumption in the operation of unit I at stage k;
X_{io}—set of possible initial states for unit i;
X_{if}—set of possible end states for unit i;
X_{ik}—State variable of unit I at stage k;
X—vector of state variables over the time horizon;
u_{ik}—integer decision variable for unit I at stage k;
U—vector of the integer decision variables over the time horizon;
p_{ik}—electrical power in unit at stage k;
d_k—electrical power associated with own consumption of electricity at stage k;
P—vector of electrical powers of the units over the time horizon;
F_{ik}—state transition function of unit i at stage k;
P_{ik}—set of possible powers for unit I at stage k;
λ—vector whose coordinates are the energy prices at each stage.

The short-term management for the conversion of biogas energy into the form of electrical energy consists of establishing a possible plan for the operation of the units, and decisions can be made in one-hour stages over a time horizon of one day to one week, corresponding to the daily cycle and the weekly cycle of electricity demand. Some data necessary for the characterisation of the short-term management are, by nature, stochastic, but given that the time horizon is short term, the estimated values are considered. Thus, the decision-making support system is described by a deterministic mathematical programming problem. The objective function is the total economic benefit obtained over the time horizon, calculated by:

$$\sum_{k\in K} \lambda_k \left(\sum_{i\in I} p_{ik} - d_k\right) \tag{2}$$

The consumption of biogas, used in the conversion, contains two parts: one determined by the amount of fuel that is required for the unit to start, i.e., the unit is brought to operating conditions that allow for the conversion of energy, and another portion, determined by the amount of fuel whose energy is actually used to be converted to the form of electrical energy. Consumption at start-up is neglected in the formulation but can easily be considered if necessary. The quantity of fuel whose energy is used to be converted into the form of electrical energy, said to be consumption with operation, is, in this communication, approximated by a Taylor series up to the second order, expressed by:

$$C_{ik}(u_{ik}, p_{ik}) = u_{ik} \left(\alpha_{ik} + \beta_{ik} p_{ik} + \gamma_{ik}/2\ p_{ik}^2\right) \tag{3}$$

The data for the parameters may differ from stage to stage, considering variations in the biogas gas mixture over the time horizon. Similarly, the level of pollutant emission of a unit will be approximated by a Taylor series until the second order, expressed by:

$$E_{ik}(u_{ik}, p_{ik}) = u_{ik}\left(a_{ik} + b_{ik} p_{ik} + c_{ik}/2\ p_{ik}^2\right) \tag{4}$$

Thus, the problem for short-term management is the maximisation of the objective function (1), which is subject to constraints such as, for example, if there is more than one unit, it can be classified into global and local. For example, limiting the level of cumulative pollutant emissions over a period is a global constraint.

Constraints can be further classified into single-stage constraints and constraints over the time horizon. An example of a global restriction involving only one stage is the limited biogas consumption in each stage for a set of Ajk units (4). On the other hand, an example of an overall restriction over the time horizon is the limited pollutant emission over the time horizon (5).

$$\underline{C}_{jk}^{req} \leq \sum_{i \in A_{jk}} C_{ik}(u_{ik}, p_{ik}) \leq \bar{C}_{jk}^{req}\ j \in J,\ k \in K \tag{5}$$

$$\underline{E}_{n}^{re} \leq \sum_{i \in B_n} \sum_{k \in K} E_{ik}(u_{ik}, p_{ik}) \leq \bar{E}_{n}^{req}\ n \in N \tag{6}$$

Local restrictions can be impositions on the value of unit state variables that are determined by the unit state transition function:

$$x_{i,k+1} = f_{ik}(x_{ik}, u_{ik}) u_{ik} \in U_{ik},\ i \in I,\ k \in K \tag{7}$$

Impositions on the power level of the units, such as power between a minimum value and the maximum possible power value, if the unit is operating, are otherwise zero:

$$p_{ik} \in P_{ik}(u_{ik})\ i \in I,\ k \in K \tag{8}$$

Impositions on possible start and end states are as follows:

$$x_{io} \in X_{io}\ x_{if} \in X_{if} \tag{9}$$

Constraints (4)–(8) define the set of plans for short-term management that are possible: $F \overset{Def}{=}$ {(x, u, p): restrictions (4), (5) . . . (8) are met} and constraints (6)–(8) define the set of plans for the operation that are locally possible, i.e., they define the set of plans that satisfy the local constraints but not necessarily the global ones.

5. Case Study

Biogas use with only one converter unit with a maximum electrical power of 400 kW was considered, with the horizon of short-term management being a day, with decisions made by the hour. Prices for electricity are shown in the "price" columns in Table A1 in Appendix A.

For the location of the MSW plant, the physical characterisation of the MSW received is illustrated in Figure 2.

The following restrictions were considered: maintaining the use in conversion over 24 h; satisfying the consumption of own electricity, the power of which is indicated in columns "d", exporting the remaining energy for sale according to the prices; and respecting the forecast of 3000 units of available volume of biogas during the 24 h period, using, in each hour, a quantity of not less than 30 and not more than 220 units of volume, with the total pollutant emissions at the end of the 24 h not exceeding 3500 mass units. Also, the following data that characterise, respectively, the biogas consumption with the operation of the unit (2) and the level of pollutant emission (3) were considered:

$$\alpha_k = 10\ \ \beta_k = 0.1\ \ \gamma_k = 0.002$$

$$a_k = 45\ \ b_k = -0.01\ \ c_k = 0.002$$

The optimal plan for the 24 h period is shown in Table A1 in Appendix A.

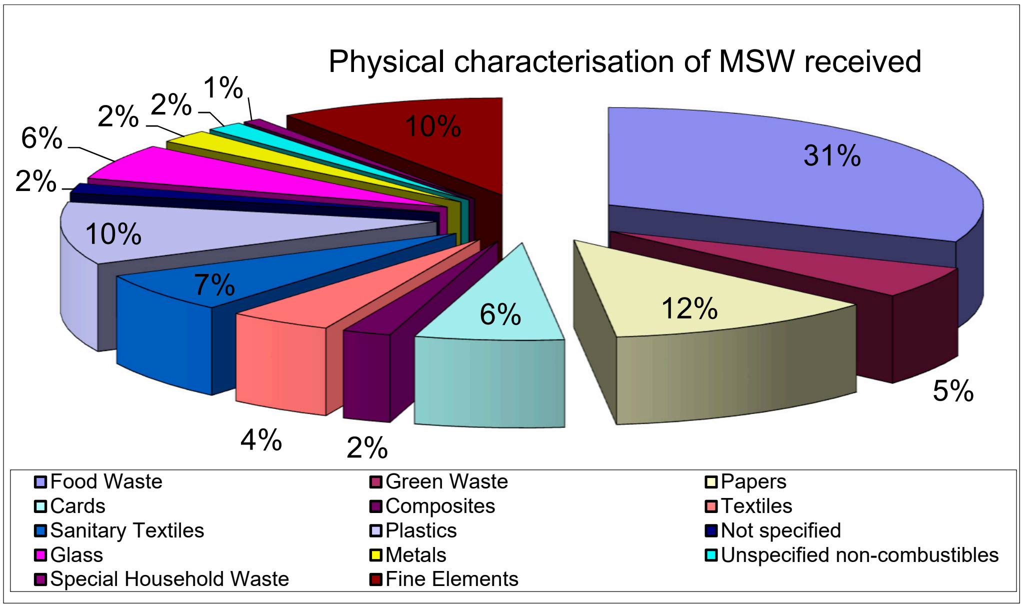

Figure 2. Physical characterisation of MSW received.

Figure 3 illustrates the evolution of prices, biogas consumption and electricity exported in each hour over the 24 h.

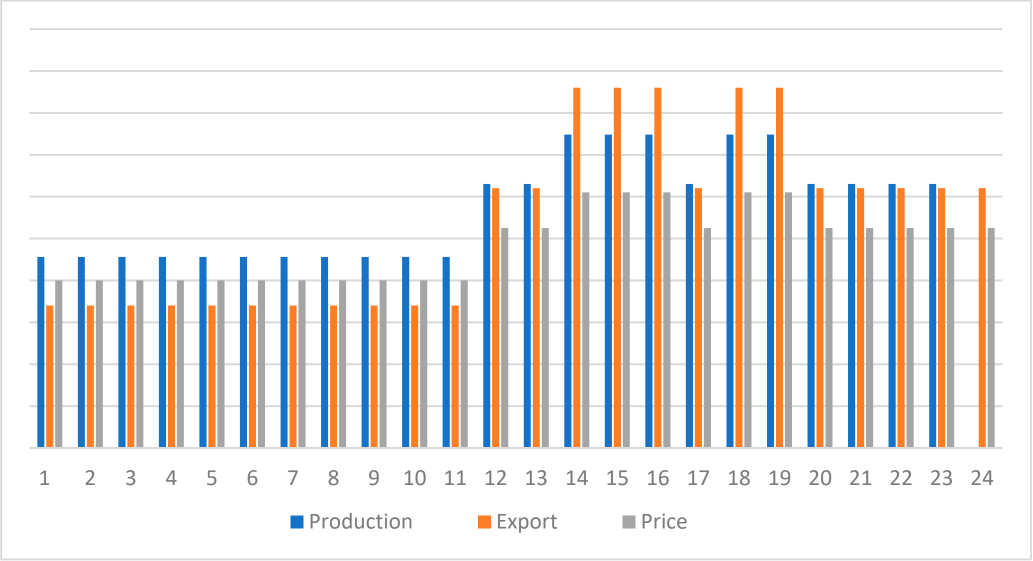

Figure 3. Price (euros), biogas consumption and electricity exports.

The revenue of sales (export electricity) is the calculation of the amount of production minus the own plant consumption multiplied by the unit price of selling.

Figure 4 illustrates the amount of CH_4 produced (in mhm^3) for the period studied (25 years).

The results allow for the conclusion that at no time should the unit be at maximum power for the proper management of the available biogas. With this computer application, not only is the excellence of the decisions supported but also the excessive use of biogas, compromising the permanence in operation of the unit due to a lack of biogas availability. Therefore, the constraints of the problem ensure the admissibility of the decision, as there is no possible decision without it. By trial and error, it is difficult to obtain the appropriate decisions or even an admissible decision that does not jeopardise the future operation of the conversion.

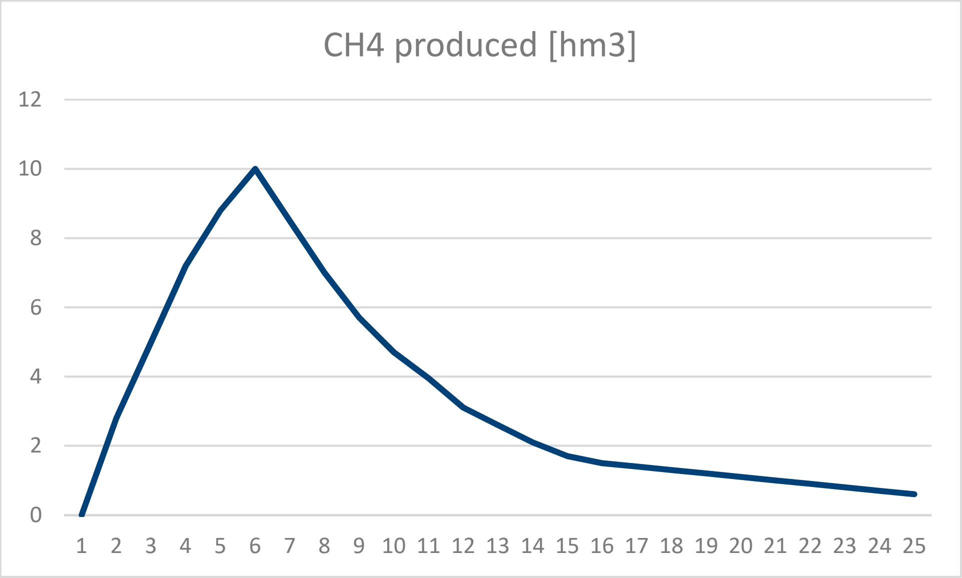

Figure 4. Amount of CH_4 produced per year, for a 25 year simulation.

A decision-making support system that allows the excellence of the economic benefit in the short-term management of biogas, considering the pollutant emissions, is presented in this communication. The system, describing the play of technical–economic mechanisms, can be formulated as a nonlinear mathematical programming problem with constraints.

6. Conclusions

Landfill gas emissions models are required to estimate the impact of landfill sites on air quality and greenhouse gas inventories. In this study, we estimated and projected the CH_4 release from an existing landfill site using models. The results highlight the importance of accurate landfill gas emissions modelling for the assessment of air quality and greenhouse gas inventories. The case study proves the ability of the LandGEM, despite some authors supporting that the Tabasaran–Rettenberger model provided a more reliable estimate, especially when compared to actual landfill data. This finding emphasises the importance of selecting models that account for the waste composition and environmental conditions of a landfill site. Nevertheless, we accept that the Tabasaran–Rettenberger model could be a valuable tool for predicting the gas production potential of landfill sites in areas with similar waste characteristics.

The advantages of this valorisation are the use of a renewable resource that has a low cost, contains lower sulphur dioxide emissions, leads to a significant reduction in global carbon dioxide (CO_2) emissions into the atmosphere, is less aggressive to the environment than fossil fuels, leads to less corrosion on equipment (boilers and furnaces, among others), consist of a lower environmental risk and is less likely to catch fire (by encouraging the clearing of forests).

The disadvantages are the lower calorific value of the biomass, difficulties in storage and the risk of overexploitation of the forest.

The results allow us to conclude that at no time should the unit be at maximum power for the proper management of the available biogas. With this computer application, not only is the excellence of the decisions supported but also the excessive use of biogas, compromising the permanence in operation of the unit due to the lack of biogas availability. Therefore, the constraints of the problem ensure the admissibility of the decision, as there is no possible decision without it. By trial and error, it is difficult to obtain the appropriate decisions or even an admissible decision that does not jeopardise the future operation of the conversion.

Future research should focus on further developing landfill gas emissions models to increase their accuracy and applicability in different landfill environments. Furthermore, examining the socioeconomic impacts and policy frameworks necessary to promote the adoption of landfill gas-to-energy production can provide valuable insights for policymakers and stakeholders. For the adequate management of this energy use, it is necessary to project the characteristics and availability of biogas and the prices of electricity. In addition, it may be necessary to retain biogas over a few hours to be used in more favourable periods.

In general, this study has highlighted the potential of this resource for sustainable waste management and renewable energy production. Biogas is a mixture that contains CH_4 and CO_2, and its energy use in the conversion to the form of electrical energy not only leads to economic benefits but also to environmental benefits, as CH_4 is more harmful than CO_2 from the point of view of the greenhouse effect. Using biogas that comes from the anaerobic decomposition of MSW deposited in landfills achieves two objectives: it reduces the emission of methane into the atmosphere through the capture and burning of biogas, as required by Decree Law No. 152/2002 of 23 May and subsequent laws, contribute to the energy recovery of waste, and increases the electricity system flexibility.

Funding: This research has received no funding.

Data Availability Statement: All the data can be provided upon request to the corresponding author Nuno Domingues.

Conflicts of Interest: The author declares no competing interests.

Appendix A

Table A1. Short-term management (24 h) optimal planning.

h	d	Gas	Gmin	Gmax	Emi	Price	p	EUR	h	d	Gas	Gmin	Gmax	Emi	Price	p	EUR
1	19	85	30	220	95	0.080	228	17	13	21	141	30	220	141	0.105	315	31
2	18	85	30	220	95	0.080	228	17	14	22	188	30	220	181	0.122	374	43
3	17	85	30	220	95	0.080	228	17	15	23	188	30	220	181	0.122	374	43
4	17	85	30	220	95	0.080	228	17	16	23	188	30	220	181	0.122	374	43
5	17	85	30	220	95	0.080	228	17	17	23	141	30	220	141	0.105	315	31
6	18	85	30	220	95	0.080	228	17	18	25	188	30	220	181	0.122	374	43
7	18	85	30	220	95	0.080	228	17	19	24	188	30	220	181	0.122	374	43
8	18	85	30	220	95	0.080	228	17	20	24	141	30	220	141	0.105	315	31
9	18	85	30	220	95	0.080	228	17	21	24	141	30	220	141	0.105	315	31
10	19	85	30	220	95	0.080	228	17	22	23	141	30	220	141	0.105	315	31
11	20	85	30	220	95	0.080	228	17	23	22	141	30	220	141	0.105	315	31
12	21	141	30	220	141	0.105	315	31	24	22	141	30	220	141	0.105	315	31
										Total	3000	720	5280	3080	—	6906	645

Here, h—hour of the day; d—electrical power associated with own consumption of electricity; gas—gas production; gmin—minimum Volume Units of gas (lower restriction); gmax—maximum Volume Units of gas (upper restriction); emi—emissions (with the total pollutant emissions throughout the week not exceeding 3500 units); price—unit price of electricity; p—optimal production of electricity; and EUR—revenue of sales.

References

1. European Commission. Commission decision of 18 December 2014, amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council, 2014/955/EU. Available online: https://eur-lex.europa.eu/eli/dec/2000/532/oj/eng (accessed on 30 March 2025).
2. Santos, M.T.; Freitas, F.; Lamego, P.; Teodoro, T. Sustainable Composting of Garden and Food Waste in Higher Education Institution. In Proceedings of the 3rd Int'l Conference on Challenges in Engineering, Medical, Economics and Education: Research & Solutions (CEMEERS-24a), Porto, Portugal, 7–8 March 2024.
3. EGF—Empresa Geral do Fomento, S.A. Feasibility study for the energy use of biogas in the Leiria Sanitary Landfill. Available online: https://www.egf.pt/en/business-areas/waste-treatment-and-recovery/ (accessed on 30 March 2025).
4. European Commission. Reducing Carbon Emissions: EU Targets and Policies. Available online: https://www.europarl.europa.eu/topics/en/article/20180305STO99003/reducing-carbon-emissions-eu-targets-and-policies (accessed on 30 March 2025).
5. European Union. Regulation (EU) 2019/1021 of the European Parliament and of The Council of 20 June 2019 on Persistent Organic Pollutants (Recast). 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX: (accessed on 30 March 2025).
6. European Commission. Circular Economy Action Plan. Available online: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (accessed on 30 March 2025).
7. European Commission. Sustainable Waste Management: What the EU Is Doing. Available online: https://www.europarl.europa.eu/topics/en/article/20180328STO00751/sustainable-waste-management-what-the-eu-is-doing (accessed on 30 March 2025).
8. Yong, Z.J.; Bashir, M.J.; Ng, C.A.; Sethupathi, S.; Lim, J.W.; Show, P.L. Sustainable waste-to-energy development in Malaysia: Appraisal of environmental, financial, and public issues related with energy recovery from municipal solid waste. *Processes* **2019**, *7*, 676. [CrossRef]
9. Atelge, M.R.; Krisa, D.; Kumar, G.; Eskicioglu, C.; Nguyen, D.D.; Chang, S.W.; Unalan, S. Biogas production from organic waste: Recent progress and perspectives. *Waste Biomass Valorization* **2020**, *11*, 1019–1040. [CrossRef]
10. EBA. Joint Statement on the Urban Wastewater Treatment Directive. Available online: https://www.europeanbiogas.eu/wp-content/uploads/2024/01/Joint-statement-Joint-statement-on-the-Urban-Wastewater-Treatment-Directive.pdf (accessed on 30 March 2025).
11. U.S. Environmental Protection Agency. International Best Practices Guide for LFGE Projects. 2012. Available online: https://www.globalmethane.org/documents/toolsres_lfg_ibpgcomplete.pdf (accessed on 30 March 2025).
12. de Leiria, C.M. IrRADIARE, Plano Estratégico de Resíduos de Sólidos Urbanos do Município de Leiria, Ref 6/24,5,240/24. Available online: https://www.cm-leiria.pt/cmleiria/uploads/writer_file/document/9927/2040603_papersu_municipio_leiria.pdf (accessed on 30 March 2025).
13. Landfill Gas Emissions Model (LandGEM). Available online: https://www.epa.gov/land-research/landfill-gas-emissions-model-landgem (accessed on 30 March 2025).
14. Domingues, N. The hidden costs of electricity and their impact in the system. In Proceedings of the 2012 International Conference on Smart Grid Technology, Economics and Policies, SG-TEP 2012, Nuremberg, Germany, 3–4 December 2012; p. 6642399.
15. Brown, M.T. Emergy and form: Accounting principles for recycle pathways. *J. Environ. Account. Manag.* **2015**, *3*, 259–274. [CrossRef]
16. Guerra, A.; de Jesus, C. *Energy Recovery of Biogas from the Leiria Landfill*; 11 ENaSB; Faro: Lake Mary, FL, USA, 2004.
17. Swana. *Comparison of Models for Predicting Landfill Methane Recovery*; Publication No: GR-LG 0075; NREL-National Renewable Energy Laboratory: Golden, CO, USA, 1997. Available online: http://www.nrel.gov/ (accessed on 30 March 2025).
18. Zheng, L.; Ma, X.; Lyu, Y.; Pan, H.; Zhang, X. Promoting synergy among environmental and economic performances in food waste treatment by optimizing biogas residue management practices. *Bioresour. Technol.* **2025**, *419*, 132101. [CrossRef] [PubMed]
19. Yuan, L.; Yang, B.; Lu, W.; Peng, Z. Carbon footprint accounting across the construction waste lifecycle: A critical review of research. *Environ. Impact Assess. Rev.* **2024**, *107*, 107551. [CrossRef]
20. Özata, S.; Değermenci, G.D. Estimation of landfill gas emissions at the solid waste disposal site of low-population regions with LandGEM and tabasaran–rettenberger mathematical models. *Energy Sources Part A Recovery Util. Environ. Eff.* **2024**, *46*, 6606–6619. [CrossRef]
21. Sarptaş, H.; Eker, S.; Seyfioğlu, R.; Boyacıoğlu, H.; Dölgen, D.; Alpaslan, N. Models for the Prediction of Landfill Gas Potential–A Comparison. In Proceedings of the International Conference on Recycling and Reuse 2012, İstanbul, Turkey, 4 June 2012.
22. Rettenberger, G.; Tabasaran, O. Recovery and Utilization of Landfill Gas at the Landfill'Am Lemberg', Landkreis Ludwigsburg. Pt. 1. Recovery and Utilization Plant. Final Report. Verwertung des Deponiegases Mit Vorausgehender Zwangsentgasung der Deponie'Am Lemberg'Landkreis Ludwigsburg. T. 1. Entgasungs-und Gasverwertungsanlage. Schlussbericht. 1986. Available online: https://www.osti.gov/etdeweb/biblio/7766819 (accessed on 30 March 2025).
23. Ominski, K.H.; Boadi, D.A.; Wittenberg, K.M.; Fulawka, D.L.; Basarab, J.A. Estimates of enteric methane emissions from cattle in Canada using the IPCC Tier-2 methodology. *Can. J. Anim. Sci.* **2007**, *87*, 459–467. [CrossRef]

24. Saeedi, M.; Mohammadi, M.; Esmaeili, N.; Niri, F.F.; Gol, H. Optimizing LandGEM model parameters using a machine learning method to improve the accuracy of landfill methane gas generation estimates in the United States. *J. Environ. Manag.* **2025**, *373*, 124029. [CrossRef] [PubMed]
25. Danthurebandara, M.; Van Passel, S.; Nelen, D.; Tielemans, Y.; Van Acker, K. Environmental and socio-economic impacts of landfills. *Linnaeus Eco-Technol.* **2021**, *2012*, 40–52.
26. Alam, A.; Chaudhry, M.N.; Ahmad, S.R.; Ullah, R.; Batool, S.A.; Butt, T.E.; Alghamdi, H.A.; Mahmood, A. Application of LandGEM mathematical model for the estimation of gas emissions from contaminated sites. A case study of a dumping site in Lahore, Pakistan. *Environ. Prot. Eng.* **2022**, *48*, 69–81. [CrossRef]
27. Tabasaran, O. Uberlegungen zum Problem Deponiegas. *Müll Und Abfall* **1976**, *7*.
28. Borgen, S.K.; Grønlund, A.; Andrén, O.; Kätterer, T.; Tveito, O.E.; Bakken, L.R.; Paustian, K. CO_2 emissions from cropland in Norway estimated by IPCC default and Tier 2 methods. *Greenh. Gas Meas. Manag.* **2012**, *2*, 5–21. [CrossRef]
29. Domingues, N. Industry 4.0 in maintenance: Using condition monitoring in electric machines. In Proceedings of the 2021 International Conference on Decision Aid Sciences and Application, DASA 2021, Sakheer, Bahrain, 7–8 December 2021; pp. 456–462.
30. Eden, C. *Garraf Landfill Site—Power Generation from Landfill Gas*; 4as Jornadas Internacionais de Resíduos: Leiria, Portugal, 2003.
31. U.S. Environmental Protection Agency. Land, Waste, and Cleanup Topics. Available online: https://www.epa.gov/environmental-topics/land-waste-and-cleanup-topics (accessed on 30 March 2025).