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Energy Use of Municipal Waste by Waste-to-Energy Technologies: Case Study of Slovakia

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ABSTRACT

The aim of the paper is to quantify the energy potential of municipal waste in Slovakia disposed in landfills and to evaluate possible alternative ways of its utilization using waste to energy technologies, namely incineration, anaerobic digestion (AD) and landfill gas generation (LFG). This paper also analyses the current state of waste management in Slovakia, creates scenarios for waste to energy recovery and compares them with the current waste management. The aim is also to identify and compare the current options and to propose the most acceptable way of utilising municipal waste in accordance with the principles of circular economy and the fulfilment of environmental objectives in Slovakia.

Keywords: Municipal Waste, Waste-to-energy, Anaerobic Digestion, Circular Economy, Energy Recovery, Waste Management
JEL Classification: O13, Q42, Q53

1. INTRODUCTION

The accelerated growth of the world economy and the high socio-economic development of the population have significantly increased the global production of municipal waste in the last decade. The main factors causing this are the growing population and increasing disposable income per capita, leading to higher consumption and consequently to the production of increased volumes of waste. According to the World Bank, global municipal waste generation has increased from over 2000 million tons in 2016 to 2200 million tons in 2024, with projected increase to 3400 million tons by 2050 (Kaza et al., 2021).

These projections of further increases in waste production in the coming years are supported by projections of the global population increasing to nearly 10 billion by 2050 (United Nations, 2022). This demographic growth, together with rising consumption rates, brings increasing pressure to improve the quality of existing but also to find new waste management systems.

Careless waste management already has serious social and environmental impacts, including pollution of air, soil and water resources, the spread of infectious diseases and the release of greenhouse gases. It is estimated that up to 75% of the world's municipal waste ends up in landfills without prior treatment (Hadidi and Omer, 2017). As is evident, the consequences of inadequate and insufficient management of municipal waste are far-reaching and can lead to acute environmental damage (Ngoc, Schnitzer, 2009).

Rapid economic growth, industrialisation and rising living standards are significantly increasing the demand for energy, resulting in an expected four to sevenfold increase in global demand for renewable energy in the coming decades (Dudley, 2019). This link between increasing energy consumption and waste production points to an acute need to find more sustainable solutions that can use waste more efficiently as an energy source and mitigate the environmental impacts of these developments.

The increasing volume of municipal waste requires the implementation of more efficient treatment methods and at the same time highlights the need for innovative approaches to waste management, that not only minimise environmental impact but also consider the principles of circular economy and sustainable development. One promising approach, that can address both problems – accumulation of municipal waste and the growing demand for energy – is Waste-to-Energy technology. This technology provides solutions in the form of converting municipal waste into usable energy through advanced methods such as incineration, gasification and anaerobic digestion. The application of these methods provides solutions to the problem of waste reduction, while promoting the production of alternative energy with a lower environmental impact.

In many countries, real solutions to the above situation mean abandoning traditional methods of municipal waste management and turning to more efficient and environmentally friendly technologies. The ability to harness the energy potential contained in waste, for example for energy production, brings about a reduction in the costs associated with the increasing volume of waste, resulting in a tangible contribution to solving both environmental and related economic problems.

The conversion of the vast amount of municipal waste into new materials and energy seems a sensible way to provide not only European Union industry domestic resources, reduce raw material imports and ultimately accelerate the transition to a more resource-efficient circular economy (European Commission, 2011). In some developed European countries, sustainable development policies have been applied for several years, with a priority focus on waste reduction and recycling, as well as its use for electricity generation (Ofori-Boateng et al., 2013).

While recycling is considered a key strategy for sustainable waste management, not all materials are recyclable, even after improvements in recycling technologies. The treatment of these residual wastes often requires difficult and costly modifications, that reduce the efficiency of individual recycling processes. It is in these cases that waste to energy (WtE) technologies are proving to be a viable alternative, enabling the sustainable recovery of both recyclable and non-recyclable materials by converting them into usable energy. The process of upgrading WtE has required more than 50 years of research and development in design and technology upgrades, making them a viable alternative to landfills and other waste disposal methods (Wilson et al., 2010).

2. STATE OF WASTE MANAGEMENT IN SLOVAKIA

Slovakia, as a central European country with an area of approximately 49,035 km^2 and a population of around 5.4 million inhabitants, represents an interesting object of study from the perspective of waste management. Approximately 2.5 million tonnes of municipal waste are produced annually in Slovakia, with an average per capita production of between 450 and 500 kg/year. Since 2018, Slovakia has recorded an annual increase in the production of municipal waste, with the exception of 2022, when there has been a slight decrease of 4.15% year-on-year. The increased growth of waste production in Slovakia is closely related to economic development and living standards, with urban areas having higher per capita waste production compared to rural regions. Compared to other European Union countries, Slovakia is one of the member states with the lowest municipal waste production (in kg per capita). However, the biggest problem with municipal waste in Slovakia is not even its increasing amount, but the very low rate of its recovery and the very high rate of its disposal in the form of landfilling.

For these reasons, we have decided in this paper to focus on municipal waste, and more specifically on the way it is managed in Slovakia. This fact is shown in more detail in Table 1, which shows that for the period from 2018 to 2022, most of the municipal waste in Slovakia was disposed by landfilling, followed its recovery through organic recovery and recycling, i.e. material recovery.

Up to 39% of municipal waste in Slovakia was disposed of by landfilling in 2022. Although municipal waste landfilling has decreased by a significant 50% from 2005 to 2022, the rate of decline is still insufficient and slow. One of the objectives of the Slovak Republic under the 2030 Environment Strategy is to reduce the rate of municipal waste landfilling to less than 25% by 2035 (Ministry of the Environment of the Slovak Republic, 2021).

In view of the above, the municipal waste was identified as the subject of the investigation and was subsequently divided into three main categories, i.e. waste with energy recovery (plastics, paper, textiles, footwear, residual waste), i.e. combustible (62.66%), waste without energy recovery (glass and metals), i.e. noncombustible (7.89%) and kitchen waste (29.46%).

3. METHODOLOGY

In order to assess the energy potential of municipal waste recovered through the selected WtE technologies (incineration, anaerobic digestion, landfilling) the mathematical models below were used, where the energy potential of municipal waste was considered as the amount of electricity generated in MWh.

3.1. Energy Recovery from Incineration

For the purpose of quantifying the potential amount of energy, that can be obtained from the incineration of municipal waste, the following relationship was used (Gómez et al., 2010; Alzate-Arias et al., 2018; Alsabbagh, 2019):

$$ERP_i = M \times LHV_{TOTAL} \times \eta \times 0.28 \quad (1)$$

Where: ERP_i – the potential amount of energy from incineration (MWh/year), M – the total amount of dry municipal waste (t/year), LHV_{TOTAL} – total lower calorific value of waste (MJ/kg), η – total efficiency of the incineration process (%), 0.28 – conversion constant MJ to MWh.

3.2. Energy Recovery from Anaerobic Digestion

The relationship below was used to calculate the electricity

Table 1: Municipal waste management in Slovakia

Item name	2018	2019	2020	2021	2022
Total municipal waste (t)	**2,325,178**	**2,369,725**	**2,596,725**	**2,705,327**	**2,597,457**
Of which: recovered materially	506,842	513,039	503,276	585, 578	531,547
Energy recovered	156,770	125,383	192,652	219,369	203,377
Recovery of organic substances	378,558	441,872	663,317	737,447	754,802
Recovered by other methods	1,713	450	2,239	18,077	19,193
Disposed of by landfilling	**1,250,280**	**1,198,249**	**1,189,239**	**1,099,288**	**1,021,584**
Disposed of by incineration without energy recovery	30,047	85,416	190	269	328
Disposed of by other methods	73	72	519	12	209
Other disposal	896	5,243	42,692	45,287	66,417

Source: own processing based on data from the Statistical Office of the Slovak Republic, 2024

generation potential of the total organic fraction of MSW in the anaerobic digestion process (Gómez et al., 2010; Alzate-Arias et al., 2019; Alsabbagh, 2019):

$$ERP_{AD} = \frac{M \times f \times M_{OFMSW} \times LHV_{BIOGAS} \times \eta \times 0.28}{1000} \quad (2)$$

Where: ERP_{AD} – the potential amount of energy from AD (MWh/year), M – the total amount of municipal waste generated (t/year), f – the fraction of the organic component (kitchen waste) in the MSW (%), M_{OFMSW} – methane production per tonne of organic component of MSW (Nm^3/t), LHV_{BIOGAS} – lower calorific value of biogas due to methane (MJ/m^3), η – overall efficiency of the AD process (%).

3.3. Energy Recovery from Landfilling

The energy recovery potential of LFG was quantified according to the following relationship:

$$ERP_{LFG} = \frac{Q_{CH4(LFG)} \times LHV \times \eta \times D}{1000} \quad (3)$$

Where: ERP_{LFG} – the potential amount of energy from LFG (MWh/year), $Q_{CH4(LFG)}$ – annual methane production in the year of calculation (m^3/year), LHV – heating value of methane (kWh/m^3),

η – the efficiency of electricity conversion (%), ƛ – efficiency of landfill methane recovery (%).

LandGEM modeling software was used to estimate the amount of landfill gas emissions (mainly methane) from municipal waste landfills, which provides an estimate of the amount of landfill gas and methane ($Q_{CH4(LFG)}$) generated over a several of planning years (U.S. EPA, 2021):

$$Q_{CH4\,(LFG)} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k \times L_0 \times \left(\frac{M_i}{10}\right) \times e^{-kt_{i,j}} \quad (4)$$

where: $Q_{CH4\ (LFG)}$ – annual methane production in the year of calculation (m^3/year), M_i – the amount of waste received in year i (T/year),

L_0 – potential methane generation capacity (m^3/T), k - methane generation rate (1/year), n – year of calculation (initial year of receipt of waste), i - 1 - annual time increment, j – 0.1 – annual time increment, $t_{i,j}$ – the age of the j-th part of the waste disposed of in the i-th year (decimal years).

RESULTS

4.1. Waste Management Scenarios in Slovakia

A total of four waste management scenarios, using different combinations of WtE processes, were established to evaluate the potential for electricity generation from all identified waste groups (combustible, kitchen and noncombustible). The different landfill waste management scenarios are shown in more detail in Figure 1. The baseline scenario was based on the actual situation in Slovakia in 2022, i.e. 1,021,584 tonnes of waste being landfilled.

In Scenario 1, it was assumed that all waste except the non-combustible waste would be incinerated together and the non-combustible waste would be disposed of in a landfill. In Scenario 2, it was assumed that food waste would be separated and recovered through AD and the other two waste streams (combustible and non-combustible) would be landfilled.

In Scenario 3, each waste stream (component) was considered using different processes. Energy from combustible materials would be obtained through incineration, while energy from food waste would be obtained through AD. Further, under scenarios three and one, it was assumed that non-incinerable materials would be landfilled, and as they do not contain any biodegradable volatiles, the potential for biogas generation for this stream of waste in landfill and hence electricity generation was not considered.

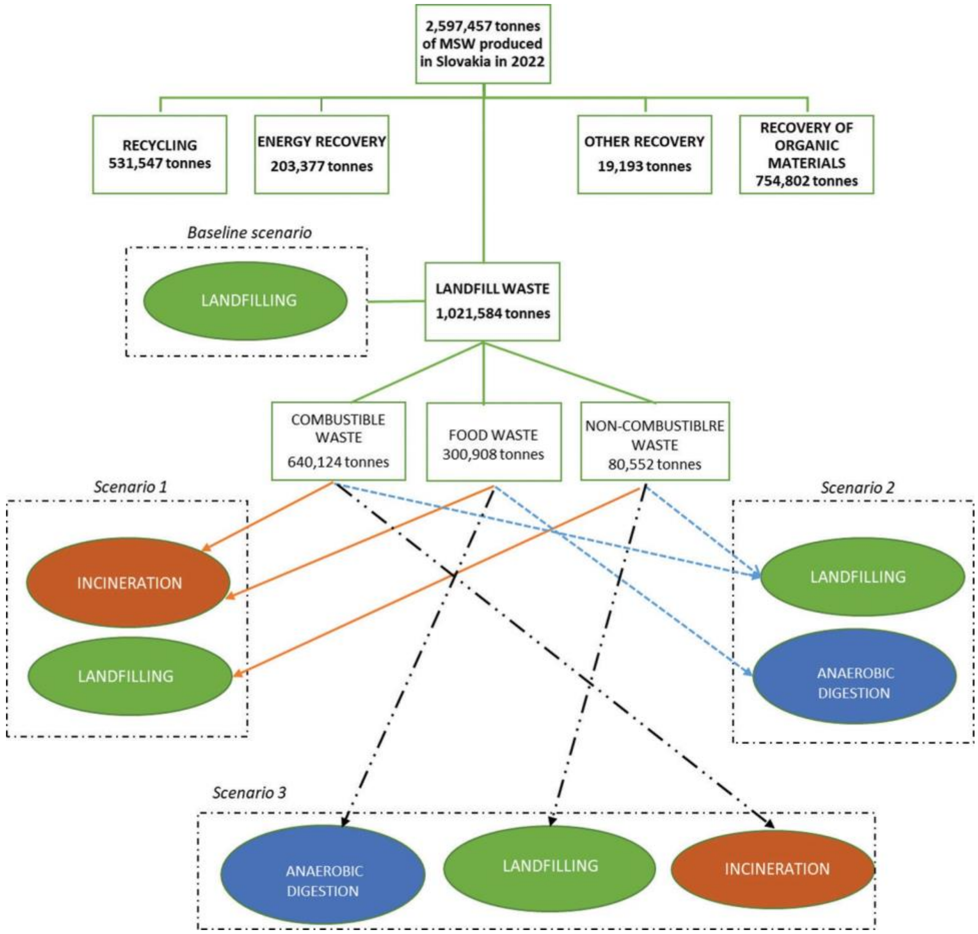
4.2. Quantification of the Potential for Electricity Generation from Municipal Waste in Slovakia

To quantify the potential for electricity generation from municipal waste in Slovakia, we analysed a total of four proposed scenarios. The energy quantifications were performed using the LandGEM model, calorimetric analyses and efficiency parameters of individual technological processes.

4.2.1. Scenario SC0 - Landfilling of Municipal Waste

Scenario SC0 aimed at quantifying the amount of electricity generated from methane produced during anaerobic decomposition

Figure 1: Waste management scenarios



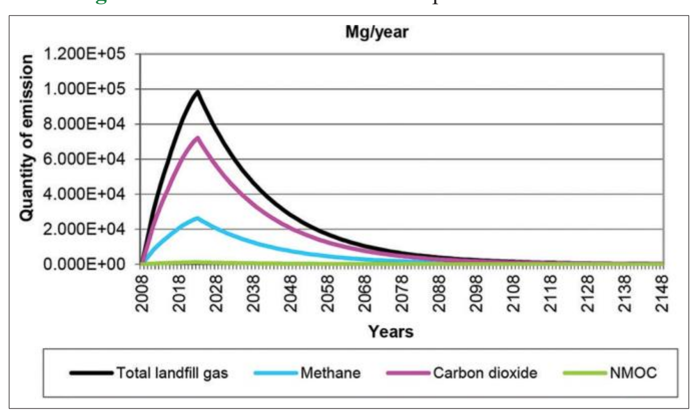
Source: own processing

of municipal waste in landfills. The LandGEM model, which is a standard tool for estimating landfill gas (LFG) emissions, was used for the calculation. This model allows the simulation of methane, carbon dioxide (CO_2) and non-methane organic compound (NMOC) production based on different input parameters.

In order to ensure the accuracy of the calculations, the input parameters of the LandGEM model (shown in Table 2) were adapted to the specifics of the Slovak Republic, namely the conditions of the dry boreal climate zone. The individual parameters included information on landfilled waste, decomposition rate of the organic component, methane generation capacity and other important factors.

The parameters presented allowed accurate modelling of landfill gas production over time, taking into account factors such as landfill age, climatic conditions and waste type. The results of the volumetric rates of LFG, methane, carbon dioxide and NMOC emissions production over a period of 140 years from the start of waste disposal are shown in Figure 2. The LandGEM model estimated methane production at 38,304,763 m^3 for the year 2022, using mathematical relationship (4). At the lower heating value of methane (10.34 kWh/m^3 - Rodrigues et al., 2022; Phyllis2, 2017; Dalmo et al., 2019; Istrate, 2022) and a collection efficiency of 80% (Alzate-Arias at al., 2019), the electricity produced was quantified at 102,870 MWh, based on relation (3) and data from Table 3.

Figure 2: LFG emissions and its components in Slovakia



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The methane-to-electricity conversion efficiency was determined to be 33%, which is a common value for landfill energy systems (Amini et al., 2013).

The results show, that the energy potential of landfill gas is relatively limited compared to other waste treatment technologies. The most limiting factor is the methane recovery efficiency, which is around 80%, while realistic values may in some cases be lower depending on the technical equipment of the landfill. In addition, environmental aspects must also be taken into account, as methane leakage into the air contributes to the greenhouse effect.

4.2.2. Scenario SC1 – Municipal Waste Incineration

The subject of SC1 was the quantification of the amount of electricity produced by the incineration of different components of municipal waste using the mathematical relationship (1). Incineration can be considered as one of the most efficient methods of energy recovery of waste, especially for combustible components such as plastics, paper, textiles and biodegradable municipal waste. The main components of municipal waste including plastics, paper, textiles, biodegradable municipal waste (BMW) and other waste were analysed to calculate the energy potential. The following data were used for quantification (Table 4).

Each fraction was rated based on its lower heating value (LHV) and its share on the total waste. In scenario SC1, the lower heating value of each waste fraction was determined based on available literature and calibrated for Slovak conditions, with a weighted average LHV of 12.2 MJ/kg. This average is also in line with average for mixed municipal waste in Europe, which ranges from 10 to 12 MJ/kg (Reimann, 2012; Saveyn et al., 2016). The total amount of dry waste destined for incineration was 615,496 tonnes in mass units. The data needed to quantify the results for scenario 1 are shown in Table 5.

Incineration efficiency of 25% (Chakraborty et al., 2013) would result in a total electricity generation of 1,571,796 MWh, which is more than 15 times the energy generated in the SC0 scenario. This result is also confirmed by the literature (Hulgaard and Vehlow, 2010), which indicates that efficient waste incineration achieves efficiencies between 20% and 35%.

The results show, that municipal waste incineration is significantly more efficient in terms of electricity production compared to landfilling. Plastics, which have the highest lower calorific value, contribute the most to the overall energy balance. Conversely, low calorific components such as mixed municipal waste contribute less to the energy balance. Incineration also offers environmental benefits in terms of reducing waste volumes and minimising greenhouse gas emissions, especially if flue gas collection and treatment systems are implemented. Despite the many advantages of this process, the environmental impacts of combustion, such as NOx, SOx and particulate emissions, must also be taken into account.

4.2.3. Scenario SC2 – anaerobic digestion

Scenario SC2 focused on anaerobic digestion, which is the biological process of decomposing organic waste in the absence of oxygen. The organic component of municipal waste in Slovakia in 2022 was approximately 29,46% of the total waste (300,908 tons). The input data for the calculations shown Table 6 and were obtained on the basis of an analysis of waste components by JRK Slovakia Ltd. To calculate the total amount of electricity, we used the mathematical relation (2).

Methane production from anaerobic digestion has been quantified at 21,364,568 m^3, which corresponds to an electricity production of 57,858 MWh at a conversion efficiency of 26% (Salah et al., 2022). This result is in line with study of Gómez et al. (2010), which states that anaerobic digestion has a lower energy yield compared to incineration, but contributes to environmental sustainability.

Table 2: LandGEM parameters

LandGEM parameters	Value	Unit	Source
Landfill open	2008	year	Own processing
Landfill closure	2022	year	Own processing
Methane generation rate (*k*)	0.05	$year^{-1}$	IPCC, 2019
Potential methane generation capacity (L_0)	60	m^3/t	Own processing
NMOC concentration	4,000	ppmv	IPCC, 2019
Methane content	50	%	Cudjoe et al., 2021

Source: Own processing

Table 3: Energy quantification results for scenario SC0

Parameters	Value	Unit
Methane production	38,304,763	m^3
Lower heating value of methane (LHV)	10.34	kWh/m^3
Collection efficiency of methane from landfills	80	%
Electrical conversion efficiency for the internal combustion engine	33	%
Electricity generated	102,870	MWh

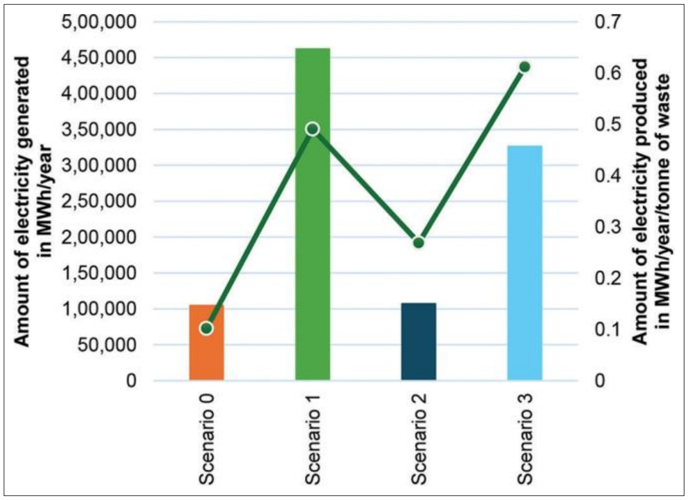
Source: own processing

Table 4: Total LHV of municipal waste

Waste category	Waste type	%	Amount (ton)	LHV (MJ/kg)	Potential energy (GJ)
Combustible	Plastics	12.48	127,443	32.35	4,123,086
	Paper	6.87	70,132	13.67	958,876
	Textiles and footwear	5.03	51,335	14.43	740,501
	BMW	16.31	166,620	14.58	2 428,491
	Other waste	21.99	224,595	3.89	873,114
	Total	62.68	640,124	-	9,124,068
Non-combustible	Glass	4.85	49,496	-	0
	Metal	3.04	31,056	-	0
	Total	7.89	80,552	-	0
Food	Food waste	29.46	300,908	14.58	4,385,727
	Total	29.46	300,908	-	4,385,727
Total LHV for MSW MIX (weighted average)				12.2	-
Total potential energy recovered					22,633,863

Source: own processing

Figure 3: Comparison of energy production by scenarios



Source: own processing

Table 5: Energy quantification results for scenario SC1

Parameters	Value	Unit
Total amount of waste	615,496	t
Average lower heating value (LHV)	12.2	MJ/kg
Efficiency of incineration	25	%
Electricity generated	1,571,796	MWh

Source: own processing

Table 6: Total LHV of municipal waste

Parameters	Value	Unit
Total amount of waste	1,021,584	t
Percentage of organic component	29.46	%
Methane production	71	Nm^3/t
Lower Heating Value (LHV) of methane	10.34	kWh/m^3
Efficiency of the AD process	26	%
Electricity generated	57,858	MWh

Source: own processing

The results obtained show, that AD has a lower energy yield compared to incineration (SC1), which is due to the limited proportion of organic waste and the lower efficiency of the process. However, AD has significant environmental benefits such as the reduction of greenhouse gases (GHG) compared to landfilling, the production of digestate, that can be used as fertilizer in agriculture and last but not least the reduction of methane emissions to the air. From an environmental point of view, AD is the preferred technology especially for the treatment of biological waste.

4.2.4. Scenario SC3 – combined approach (AD, landfilling and incineration)

Scenario SC3 combined all three technologies: landfilling, incineration and anaerobic digestion using the mathematical relationships mentioned above. The total electricity generation potential for this scenario was 385,073 MWh, with the largest share for incineration (327,214 MWh), followed by anaerobic digestion (57,858 MWh), while the contribution from landfill gas is 0 MWh, as it is assumed that the waste is efficiently recovered by other technologies.

It can be concluded, that the combined approach maximises the energy yield by optimising the use of the different waste fractions. The key benefits of SC3 include efficient use of waste for energy purposes, reduction of landfill waste and reduction of greenhouse gas emissions compared to traditional landfilling.

5. DISCUSSION

The results of the conducted analysis showed that different technological approaches to municipal waste processing vary significantly in the amount of electricity they can generate. The findings indicate, that SC1 (waste incineration) achieves the highest electricity production, both in total amount (1,571,796 MWh/year) and in energy generated per ton of waste (2.46 MWh/t). Therefore, this scenario is the most efficient in terms of energy yield. On the other hand, SC0 (landfilling) exhibits the lowest rate of waste-to-energy conversion. Although some landfill gas can be captured, a large portion of the waste's energy remains unused. The result of 0.10 MWh/t of waste demonstrates that landfilling is not an effective energy source. It was confirmed, that SC1 (incineration) achieves the highest energy efficiency per unit of waste. The average value of 2.46 MWh/t of waste confirms, that incineration is highly effective in converting waste into electricity. This scenario is therefore the most suitable, where the goal is to maximize energy production. In contrast, SC2 (anaerobic digestion, AD) is less efficient in terms of energy yield, than incineration but remains more advantageous than landfilling. The resulting value of 0.19 MWh/t suggests that AD can produce nearly twice as much energy per ton of waste compared to landfilling. Scenario SC3 (a combined approach) appears to be a compromise between incineration and AD. The production of 0.41 MWh/t of waste indicates that combining different technologies enables a better energy yield than individual technologies alone. This optimizes waste utilization while also reducing the environmental impacts of landfilling and incineration. Comparison of the total energy produced according to each scenario shows Figure 3.

Foreign studies support our findings. In Bangladesh, incineration achieved 0.43 MWh/t, while in Thailand, it reached 0.48 MWh/t. Combined approaches in Italy and China confirmed high efficiency (Zhou, Zheng, Huang, 2017), whereas AD demonstrated environmental benefits in countries such as Brazil (0.21 MWh/t) and Nigeria (0.19 MWh/t). These results further reinforce our own findings that combining technologies enhances energy efficiency while simultaneously minimizing environmental impact.

6. CONCLUSION

The increasing amount of municipal waste and the rising energy demands in Slovakia underscore the need for the efficient use of Waste-to-Energy technologies. These technologies represent a significant alternative to traditional landfilling, which has low energy efficiency and a negative environmental impact. The conducted study confirms that waste incineration is the most effective method of energy recovery, while anaerobic digestion is suitable for processing biodegradable waste. The combined approach (scenario 3) proves to be optimal due to its high energy output and its ability to process diverse waste streams.

Based on the comparison of the amount of electricity generated, it is essential to minimize the share of waste sent to landfills in Slovakia as soon as possible, as this scenario achieves the lowest energy recovery rate. Conversely, it is necessary to increase the share of waste incineration (SC1) in combination with other technologies, especially in areas with enough non-organic waste suitable for incineration. Furthermore, anaerobic digestion (SC2) should be promoted for organic waste, as it enables the energy recovery of biodegradable waste while also producing digestate suitable for agricultural use. Additionally, implementing combined solutions (SC3) allows for optimized waste utilization based on its composition, maximizing electricity production while minimizing environmental impacts.

The conclusions of our study clearly confirm the urgent need for a swift transition to WtE technologies in Slovakia, not only for efficient waste management but also to enhance energy self-sufficiency and reduce environmental burden. The rapid implementation of these technologies will not only support the circular economy but also contribute to achieving Slovakia's environmental goals.

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