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Waste-to-Energy Generation: Complex Efficiency Analysis of Modern Technologies

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Abstract: Recycling of Municipal Solid Waste (MSW) is a significant challenge all over the world. Waste-to-Energy generation solves the problem of MSW recycling and produces power for urban territories. In this study, the researchers implemented complex economic and ecological efficiency analyses of modern Waste-to-Energy technologies. The fundamental challenge of modern Waste-to-Energy generations is finding the balance between economics, ecology, and productivity. Thus, to assess the effectiveness of various thermal technologies, statistics from enterprises were used. The Balanced Scorecard (BSC) method was implemented to calculate an integral effectiveness of a particular Waste-to-Energy technological approach. Environmental and economic analysess of thermal MSW disposal technologies was carried out by selecting the data from at least 146 functioning plants in Canada, China, Finland, France, Germany, Italy, Japan, the Netherlands, Sweden, and Thailand. The research results confirm that gasification technology was the most promising and the most environmentally and cost effective. Incineration Moving Grate technology was the least effective and attractive Waste-to-Energy technology according to the results of the environmental and economic efficiency assessments. The research results can be used for urban planning in waste recycling projects and the new energy national and municipal agenda. The research results can also be useful for municipal strategic energy and sustainable plans and programs.

Keywords: Waste-to-Energy; waste management; green energy; sustainability; renewable energy sources; municipal solid waste (MSW); MSW disposal; MSW combustion facilities; energy treatment of MSW

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1. Introduction

Solid municipal waste management (MSW) is an integral part of human activity. Poor MSW leads to serious environmental problems and affects the health and lives of people. This ultimately slows down economic growth; society needs to create a well-thought-out infrastructure around MSW [1]. The issue is becoming more serious and requires more rapid action as incomes, consumption and urbanization levels are increasing, and consequently, so are the volumes of generated waste.

Waste-to-Energy projects support such global sustainable development goals (SDG) as SDG 7 "Affordable and clean energy" and SDG 11 "Sustainable cities and communities" [2]. Recycling municipal solid waste (MSW) also leads to SDG 11. Energy generation from MSW opens up alternative energy sources for cities, especially in regions lacking in natural energy resources. The development of Waste-to-Energy generation networks stimulates sustainable development in urban territories. Concern about the MSW is also reflected in the UN reports, and the COVID-19 pandemic has complicated it further for municipalities that require not only the development of an existing waste treatment system, but even their preservation [3,4].

The worsening of the problem is illustrated by a World Bank report, according to which the total annual volume of waste generated in 217 countries will grow by 1.6% per year, relative to the 2016 level of 2.01 billion tones, and will reach 3.4 billion tones by 2050. The world's most common and affordable type of MSW disposal remains landfills, which has the greatest negative impact on the environment (Figure 1). One of the many ways to improve waste management is the utilization of wastes to generate power. This was hailed as a renewable energy source about thirty years ago [5]. The choice of the most effective among popular thermal MSW treatment technologies seems regularly difficult due to the wide variety of indicators that need to be considered for a strategic and holistic comparison. One of the basic trends in the efficiency analysis of MSW energy utilization facilities is an enterprise's life cycle assessment or the region's development plan [6,7]. Another popular direction is the investment feasibility assessment of energy generation from MSW, based on the net present value or a comparison of the total capital and operating costs [8,9]. Research has considered the attractiveness of environmental and economic technologies earlier, but the conclusions have only been drawn for single examples, such as two Argentinian city case studies [10].

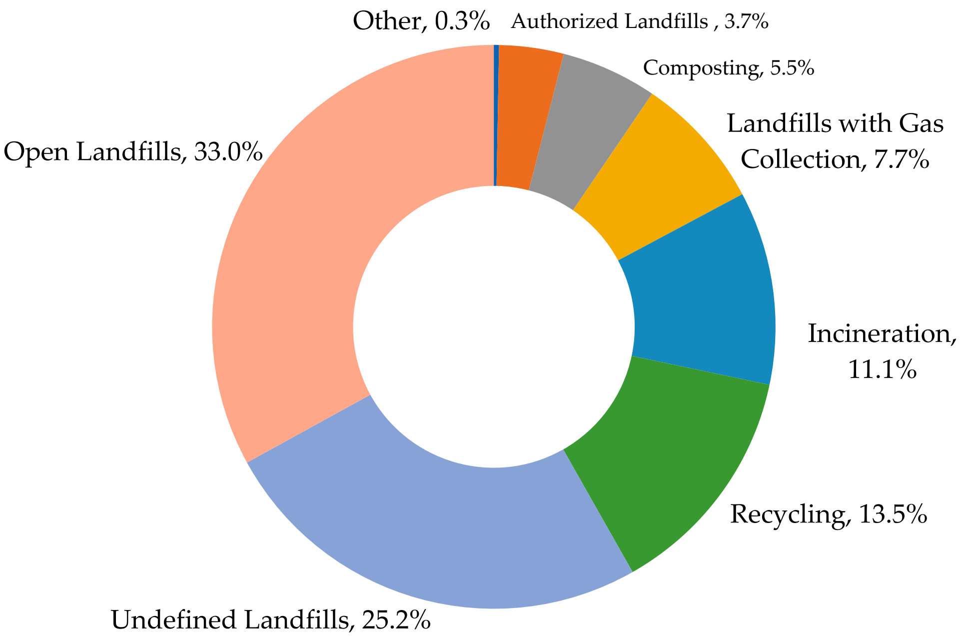

Figure 1. Global MSW treatment methods, %. Source: Compiled by the authors based on World Bank, 2022 [11].

This study aims to fill the gap in the literature by considering the equivalent environmental and economic factors and to assist decision-makers in the development of thermal MSW management. In light of the aspects mentioned above, the authors set the goal of comparing the environmental and economic efficiencies of popular thermal energy generation from MSW methods.

The research hypothesis is that even though incineration on a grate is the most economically viable technology and is widespread, the most promising and environmentally friendly is the innovative method of plasma gasification.

2. Critical Review of Energy from MSW Technologies

2.1. MSW Handling Methods

American (United States Environmental Protection Agency), European (European Environment Agency) and intergovernmental (United Nations) regulators define MSW as waste generated in domestic, commercial, and industrial premises, by public institutions such as schools, prisons, as well as in communal areas including streets, bus stops, etc. [4,12,13].

In practice around the world, MSW handling methods are historically ranked by Lansink's Ladder ([14]). First described in 1979 by the Dutch politician Ad Lansink, the hierarchy has been transformed into a modern classification of ways to manage waste from the least attractive to the most preferred, depending on the sustainability of the method.

The oldest, most common, and least preferred method of handling MSW is at landfills [15]. European countries are actively reducing their share of solid waste disposal, which is reflected in the annual 4%–5% share growth rate of the other more environmentally friendly waste management methods: Recycling, incineration, and composting (Figure 2). This happened thanks to the European Framework Directive on Waste, which set a goal for member countries to reduce biodegradable MSW sent to landfills by 75%, 50%, 35% and 10% by 2006, 2009, 2016 and 2035, respectively [16].

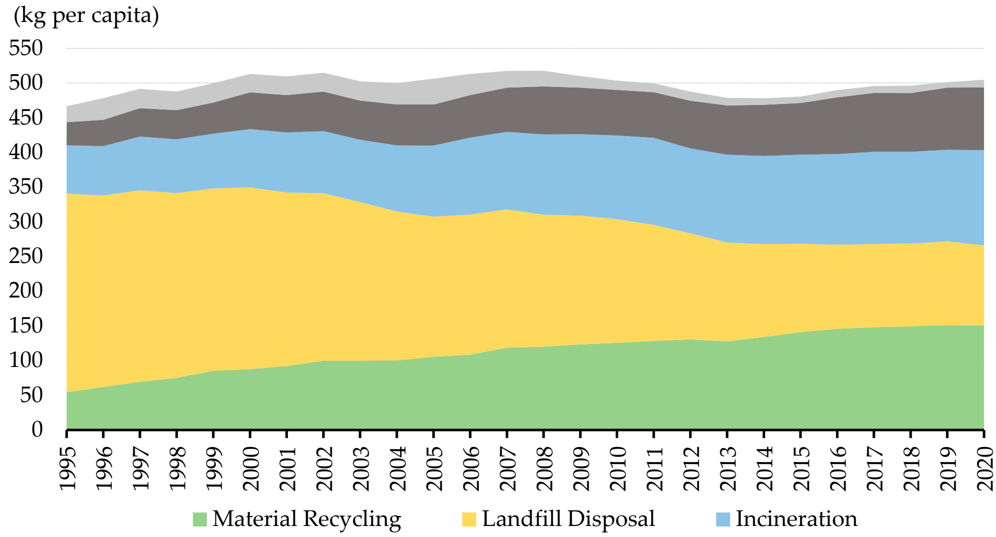

Figure 2. Main MSW treatment methods in EU-27 from 1995 to 2020. Source: Compiled by the authors on the basis of Municipal Waste Statistics, 2021 [17].

The fifth rung is the incineration of MSW, which is the less efficient burning of waste. Depending on the technology used, this has an ambiguous effect on CO_2 emissions. Those incinerators that work with insufficiently prepared waste containing hazardous or recyclable materials, operate at relatively low combustion temperatures, or need a more rigorous filtration process (the reduction of heavy metals and dioxins in the exhaust mass), not only have a negative impact on the environment, but even pose a direct threat to the health of workers and the local population [18].

Efficient energy generation is the fourth rung of the Lansink's Ladder. MSW handling method is also called Waste-to-Energy and includes various technological solutions. In modern practice, three main types of heat MSW treatment are prevalent: Incineration (on a mechanical moving grate, in a circulating fluidized bed, or in a rotary kiln), gasification (conventional or plasma) and pyrolysis (oxidative or dry, fast or slow, and microwave pyrolysis) [19].

2.2. MSW Heat Treatment Types

Consider three existing thermal methods in descending order of their popularity [20]. In all regions, the dominant incineration technology is currently moving grate because of its historical superiority and proven advantages [21,22].

2.2.1. Incineration

The mass feeding method used during combustion on a moving grate eliminates the need to pre-process waste carefully, being limited to sieving and loosening [23]. Complete oxidative incineration in this case occurs at a temperature of 700–1200 °C.

The next common combustion technology is a circulating fluidized bed. The process temperature is the lowest in comparison to the other two technologies considered here and does not exceed 1000 °C and involves an ascending air flow entry into the furnace chamber at high speed, which creates a kind of boiling fluid from MSW particles [24]. For incineration using this technology, waste must be pre-sorted and shredded. Another disadvantage is the need to limit the combustion temperature to prevent the particles from sticking together, which simultaneously reduces the resulting fuel energy value and leaves more dangerous flue gases.

The rotary kiln follows in terms of popularity. Incinerators with this technology can process safe solid and harmful liquid waste due to the secondary treatment presence in the form of afterburners [25]. The combustion temperature lies in the range of 800–1300 °C, taking into account the purpose of the furnaces and the degree of the hazard of the waste. It is the most capital-intensive technology in the combustion group.

2.2.2. Gasification

Another group of MSW heat treatments is gasification, that is, the partial oxidation of prepared organic substances (or in another gasifying medium) [26]. Conventional gasification is a more well-known method and transforms waste into synthetic gas (syngas) with its subsequent conversion into thermal energy by burning raw syngas or into electrical energy after purification. The temperature range is 1000–2000 °C, which is affected by the gasifying agent.

A more modern and innovative subset is plasma gasification, which is carried out at 3000–14,000 °C [27]. Due to such an extremely high temperature, either complete decomposition of waste is ensured or no more than 7% non–toxic ash and slag, which are suitable materials for construction. However, the technology only has a medium level of maturity, namely because of society's ignorance about the potential risks of high-temperature processes, the lack of a regulatory framework for plasma gasification plants, and the complexity of field efficiency assessment due to the small number of enterprises in operation.

2.2.3. Pyrolisys

The third thermal option is pyrolysis, which differs from gasification because of the absence of oxygen during the waste decomposition at relatively high temperatures with pyrolysis gas production. Anaerobic processes make it possible to use temperatures of 200–500 °C and generate a large amount of thermal energy [28]. Pyrolysis is relevant if there is a need to extract processed products; they can be gaseous substances, liquid (tar) or solid (char) [29]. This is facilitated by its two-stage process nature.

We have reviewed the existing thermal technologies for the energy MSW utilization. Now consider the statistics on thermal processing use in practice. According to the EcoProg report, Waste-to-Energy has developed in 2021. The total number of incinerators and associated power plants installed during the year exceeded all previous figures, and there were 130 new facilities with thermal technologies with a total annual MSW capacity of 41 million tonnes, 78% of which are in China [30]. A 7% contribution was made by European countries, but the generation of the development is also taking place in other regions. As a result, the total thermal waste processing plants number in the world is now 2580 units, and their cumulative annual MSW capacity is 456 million tonnes.

3. Materials and Methods

To calculate an effectiveness assessment of a particular Waste-to-Energy method, we turn to the Balanced Scorecard (BSC). BSC is a strategic management tool and has previously been used in MSW research to assess the effectiveness of waste management systems in general, but not specific plants [31,32]. Nevertheless, a modified BSC seems to be a relevant way to consider the environmental and economic characteristics of thermal MSW disposal technologies.

3.1. Establishing the Dataset Frame

To assess the effectiveness of various thermal technologies, we searched for statistics from functioning enterprises. We used a list of MSW generating plants with background information about incinerators and their technical characteristics, collected in 2020 [33]. Coenrady registry was exclusively accurate for this paper's purpose because it contains regularly updated basic information on the plants' emissions under consideration. We added a parameter necessary for our analysis, namely the type of thermal technology (Type). Additionally, we also created a code (Code) that matches the serial number of the plant in the registry.

3.1.1. Economic Variables Defining

For the analysis of economic efficiency, we calculated the return on investment (ROI) coefficient in the simplest form with attention paid to the analysis specifics, which considered the income and expenses of the generating enterprise [34]. We collected the annual revenue (Revenue) and expenses (Expenses) according to the company's profit-and-loss statement and applied Equation (1).

$$ROI = \frac{Revenue - Expenses}{Expenses} \times 100\% \tag{1}$$

In addition, we prepared data on the volumes of diesel fuel in liters (Diesel_ash) and electricity in kilowatt-hours (Electricity_ash) consumed per MSW tonne for ash and slag management. We treated waste pretreatment (Pre-treatment) as a binary variable due to the difficulties of financial cost comparisons. All monetary values were converted to US dollars at the current international exchange rate at 25 May 2022.

3.1.2. Environmental Variables Defining

For the environmental efficiency analysis, we supplemented the data with the following indicators: The plant processing capacity in MSW annual tonnes (Capacity), the efficiency of generating electricity and/or heat in percentage (EER and/or HER), and the energy efficiency calculated using the European Waste Framework Directive methodology (EE_EU), Equation (2).

$$EE_{EU} = \frac{E_p - \left(E_i + E_f\right)}{0.97 \times \left(E_w + E_f\right)} \times CCF, \tag{2}$$

where E_p is all the energy produced (GJ/year);

E_i is imported energy (GJ/year);
E_f is energy consumed from fuels other than MSW (GJ/year);
E_w is energy from MSW (GJ/year);
CCF is the climate correction factor [35].

Next, we noted the average annual emission rates in milligrams per cubic meter, unless otherwise stated; fine dust (Dust), sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), total organic carbon (TOC), hydrochloric acid (HCL), hydrogen fluoride (HF), heavy metals (Metals), mercury (Hg), dioxins toxic equivalence in nanograms on standard cubic meter (PCDD/F), and cadmium in milligrams per normal cubic meter (Cd).

Finally, we integrated previously conducted case studies based on the life cycle assessment tool (LCA). The complete set of seven LCA-coefficients for MSW generating facilities reflects the environmental impact of each pollutant category: Global warming (GW), acidification (AC), terrestrial eutrophication (TE), photochemical ozone formation harmful to human health (POFh), human toxicity via air (HTa) and via solid (HTs), and ecotoxicity via solid (ETs) [36–38].

3.2. Collecting the Data

The limited number of LCA-studies, the need for publicly available company financial reports, and the complexity of objective comparison of the above-mentioned indicators dramatically reduces the waste processing plant data. At least 146 companies from Canada, China, Finland, France, Germany, Italy, Japan, the Netherlands, Sweden, and Thailand were included in the final dataset. We gave a brief description of the observations and additional data sources (if applicable).

Dong et al. considered four operating plants and seven scenarios, which we aggregated into four groups (grate incineration, pyrolysis, gasification, and plasma gasification), since we did not examine different types of engines [39].

Data for the Italian grate incinerator Silla2 (Code 916) on the 2021 capacity, energy efficiency, and Dust, TOC, HF, Metals, revenue, and expenses were added from the company website (for three operating facilities), and the annual plant and the parent company reports [40–43].

In Germany (Code 567), the Müllverbrennungsanlage Hamm plant with pyrolysis technology was selected; capacity, energy efficiency, missing emission Dust, HF, and Metals indicators were collected from the enterprise website and the annual report on all four functioning lines [44,45]. Revenue and balance sheet data were found in open sources and the Unna district report [46,47].

Information on capacity, Dust, TOC, and HF was added to the data on Finnish Westenergy MSW gasification plant (Code 670) from the company's website and the annual report [48,49].

The Japan case (Code 1395) involved plasma gasification at two Nagoya Nippon Steel installations. The capacity and financial indicators were taken from the parent company's website and the corporation's U.S. Securities and Exchange Commission report [50,51].

Another object was the VantaanEnergia plant in Finland (Code 678) with gasification technology [52]. Capacity and financial indicators were listed on the official website and in the company's financial statements, and energy efficiency data were provided in the engineering company prospectuses [53–55].

The authors also examined the Högdalenverket plant in Sweden (Code 1961) with rotary kiln incineration technology (in six boilers). The capacity was given on the plant's website, the financial indicators were listed in the annual report, and energy efficiency data were in the sustainable development report [56–58].

Add a small Italian factory AceaAmbiente Terni with pyrolysis technology (Code 938) to the analysis [59]. The one-line capacity, as well as the Dust, SO_2, NOx, CO, TOC, HCL, HF, Metals, Hg, and PCDD/F parameters were presented on the company website and in the report [60,61]. The subsidiary plant financial indicators were listed in the parent corporation accounting statements [62].

Another plant (Code 1876), Afval Terminal Moerdijk, with pyrolysis technology on four streams was studied in the Netherlands [63]. Statistics on capacities were obtained from the official website and financial indicators from the parent company report [64,65].

Rotary kiln technology was considered for the Phuket I Thai incinerator (Code 1981) [66,67]. The researcher for the Phuket incineration infrastructure and the municipality provided the capacity, electricity generation efficiency, and financial indicators [68,69].

In their study, Jun Dong and colleagues provided an aggregate ratio of 85% of plants in France (Code 2117) and most generating enterprises in China (Code 2118) with incineration on a grate and in a circulating fluidized bed, respectively [70].

Mayer and colleagues averaged the grate combustion across Germany (Code 2119) and assumed no pre-sorting and drying of MSW [71].

For seven standard Canadian plants (Code 2120) with rotary kiln technology, we converted the emission statistics into our scale by multiplying the emissions amount per 1 MSW kg by the daily plant capacity and 365 days a year [72].

3.3. Preparing the Data

To improve the sample quality, the missing efficiency values of electric and/or thermal energy generation (Code 678, 1961) were filled in based on averaged data collected in 2018 for thermal combustion and gasification technologies [73,74]. We completed revenue and expenses data through a review of several studies grouping the data by incineration type and calculating the average (Code 2117, 2118, 2119, and 2120) [70].

Missing Diesel_ash and Electricity_ash indicators (Code 678, 938, 1876, 1961, 1981, 2119, 2120) were taken from the aggregated cost analysis for three types of thermal MSW treatments [39].

Omissions of emissions (Dust, TOC, HF, Metals) from plasma gasification were eliminated using economic analysis data from 2010 of a similar Canadian installation (Code 1395) [75]. Most of the lacking emissions (Dust, TOC, PCDD/F) for other technologies are calculated based on similar installations from a 136 LCA studies review [76]. The remaining blank cells were filled with the average values in the technological group.

The preliminary data processing was completed, first by grouping observations by thermal technology type. Next, six groups were studied on average: Incineration on a moving grate (Incineration moving grate), in a rotary kiln (Incineration rotary kiln), in a circulating fluidized bed (Incineration fluidized bed), conventional gasification (Gasification), plasma gasification (Plasma Gasification), and pyrolysis (Pyrolysis), i.e., without reliance on specific factories. Secondly, the last preparation stage was the mini-max data normalization to the range from 0 to 1 by Equation (3).

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{3}$$

3.4. Assigning Weight to the BSC Parameters

Finally, we applied BSC to the assembled dataset. We distributed the weights between the created parameters characterizing the MSW processing methods effectiveness. To begin with, 50% (Analysis weight) was obtained by two main groups (Analysis): total economic and environmental parts. We believe that these two types of efficiency are equally important since this paper aimed to evaluate both. Next, we highlighted ROI with a 40% weight (Indicator weight) as it was the most significant indicator (Indicator) in the economic group. Waste pre-treatment, as a parameter that reduces economic efficiency (Pre-treatment), received 8%, and the ash management costs (Diesel_ash, Electricity_ash) obtain 1% each.

The environmental group included three subgroups and a capacity indicator (Capacity), which was given 4% impact because large processed MSW volumes are a more environmentally friendly solution than the alternative next Lansink's Ladder steps.

The first subgroup (Environmental_Efficiency) combined energy production efficiency indicators (EER, HER, and EE_EU) and distributed 12% between them: 4% were distributed between three parameters or 6% between the two in the case of thermal energy generation (HER) absence at the enterprise. The second (Environmental_Emissions) and the third (Environmental_LCA) subgroups received 17% of the negative impact and included eleven equivalent emission indicators and seven life cycle assessment parameters. Similarly, we distributed the percentages expertly, assigning approximately the same significance to the indicators.

Thus, multiplying the indicator weight by its value (Value) for each type of thermal technology and taking into account the impact direction, namely negative or positive, provided an intermediate influence assessment of the parameter on the desired multifactorial technology efficiency. The sum of intermediate values (SUM) is an integral ecological and economic efficiency index, and their relation to each other for all considered Waste-to-Energy practices was the result of this study.

4. Results and Discussion

4.1. Calculating Integral Efficiency Indicator

First, a set of environmental (Appendix A) and economic (Appendix B) indicators is obtained for a comprehensive comparison of the various thermal Waste-to-Energy technologies effectiveness.

The second result is an integral index for each of the six thermal waste treatment technologies (Appendix C). Ordinal comparison of these values opens up the possibility of collating the multidimensional efficiency of six technologies (Table 1).

Table 1. Comparative environmental and economic efficiency analysis of the MSW thermal energy treatment technologies.

Analysis	**Analysis Weight**	**Assessment for Incineration Moving Grate**	**Assessment for Incineration Rotary Kiln**	**Assessment for Fluidized Bed**	**Assessment for Gasification**	**Assessment for Plasma Gasification**	**Assessment for Pyrolysis**
Economic	0.50	−0.008	0.067	0.305	0.213	0.068	0.095
Environmental_Capacity	0.04	0.040	0.024	0.000	0.015	0.008	0.028
Environmental_Efficiency	0.12	0.040	0.076	0.001	0.105	0.022	0.070
Environmental_Emissions	0.17	−0.078	−0.077	−0.062	−0.018	−0.055	−0.051
Environmental_LCA	0.17	−0.062	−0.112	−0.070	−0.071	−0.032	−0.047
SUM	**1.0**	**−0.067**	**−0.023**	**0.174**	**0.243**	**0.012**	**0.095**

4.2. Comparative MSW Heat Methods Analysis

According to the calculations, plants with a fluidized bed or conventional gasification are the most economically attractive. The main outsider in this category is the incineration on a moving grate. This can be explained by the fact that the technology appeared first among all thermal methods, and accordingly, most installations are outdated and worn out. Thus, processing companies receive low revenues [77]. Moreover, the capital expenditures' comparison for the construction of a new plant with a moving grate or with economically leading fluidized bed also shows the second option's greater rationality.

However, the incineration in a fluidized bed turns out to be lagging in two environmental clusters at once because the enterprises consider processing the smallest MSW volumes and have the lowest energy generation efficiency in the group (Figure 3). Another reason is that only ordinary Canadian plants are listed in the dataset, i.e., those that are not ahead of enterprises with a moving grate if we compare the fixed assets depreciation level.

Enterprises with moving grate technology process the largest MSW volumes and release the highest emissions amount into the environment. As a result, owing to the relative economic inefficiency and high pollution level, this technology ranks last among those considered by the final integral indicator. This is followed by incineration in a fluidized bed, which also has a relatively high negative ecological impact.

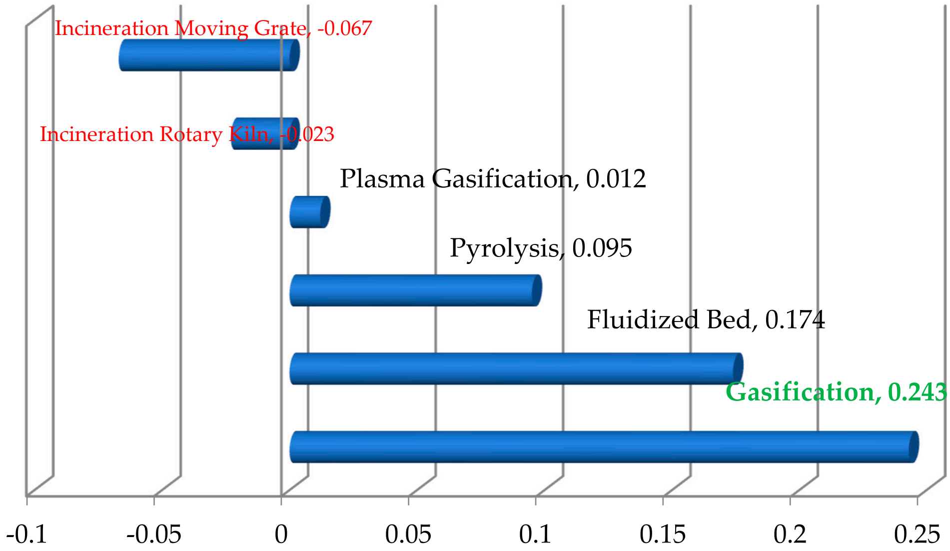

Figure 3. The total performance BSC indicator of environmental and economic efficiency. Source: Compiled by the authors.

Currently, the undisputed leaders in the energy generation sustainability are gasification and plasma gasification. Eventually, conventional gasification becomes the final integral index leader thanks to the lowest emissions, the best production efficiency, and high economic profitability (second place among all technologies). At the same time, the LCA-identified relatively low gasification success does not coincide with the assessment carried out on a smaller number of observations in 2013 [78]. Thus, for Russia's Kaliningrad region, the environmental and economic prospects of the most modern plasma gasification are also highly appreciated [79].

Pyrolysis takes an average ranking position, although it is noted as a promising method in a number of studies [80]. Among its advantages are relatively low pollutions and its disadvantage is the need for careful preliminary waste preparation [9].

The environmental and economic analysis based on the integral indicator from BSC points at the gasification technology as the most effective method of thermal MSW energy practice. This study's prospects consist, firstly, in expanding the observations and adding statistics of other functioning plants to the integral indicator calculation for greater accuracy. Secondly, thanks to scientific LCA-works of non-thermal technologies for generating energy from MSW (extraction of landfill gas or biogas by anaerobic digestion with further composting), new opportunities open up for comparing all MSW treatment options, not just thermal ones [81]. In future research, it will be possible to enrich the research methodology with other elements of multi-criteria analysis of waste management [82].

5. Conclusions

A comprehensive analysis of the environmental and economic efficiency of 146 operating plants processing MSW into energy from Canada, China, Finland, France, Germany, Italy, Japan, the Netherlands, Sweden, and Thailand for the period 2004–2021 demonstrates the following findings:

According to the results of the environmental and economic efficiency assessment by Balanced Score Card (BSC) methodology, incineration Moving Grate technology is the least effective and attractive. Incineration Rotary Kiln technology is also in the negative zone by calculations. Consequently, their use and development are unpromising according to the research results.

Gasification technology is the most promising and the most environmentally and cost effective by BSC assessments. This technology of combustion in a circulating fluidized bed is defined as the most economically justified and a relatively modern method of conventional gasification becomes the most environmentally friendly. This is a promising and green technology that can significantly improve the sustainable development of urban areas and contribute to the achievement of SDG 7 "Affordable and clean energy" and SDG 11 "Sustainable cities and communities" at the municipal level.

It should be noted that Fluidized Bed technology is also promising for the development of Waste-to-Energy projects. This technology is not significantly lagging behind leaders, according to the research calculations. For better results, it should improve its environmental efficiency. Such technologies, such as pyrolysis and plasma gasification, should be further improved for leading modern green technologies in the waste-to-energy sector.

The research results can be used globally for urban planning in waste recycling projects and a new energy agenda. In addition, the study can be useful for municipal strategic plans and programs.

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Appendix A. A Set of Environmental Indicators for MSW Heat Treatment Enterprises

Appendix A.1. Enterprises' Capacity and Efficiency Indicators

Code	Type	Capacity	EER	HER	EE_EU
				Efficiency	
-	categorical	tones annually	%	%	-
567	Pyrolysis	287,000	22.0	-	0.8000
670	Gasification	193,675	27.4	61.4	0.9410
678	Gasification	374,000	47.0	45.0	0.9500
916	Incineration moving grate	500,000	24.2	5.5	0.8980
938	Pyrolisys	120,000	18.0	-	0.8000
1295	Plasma Gasification	193,450	23.0	-	0.6046
1876	Pyrolisys	1,000,000	-	70.0	0.8000
1961	Incineration rotary kiln	700,000	11.0	73.0	0.9100
1981	Incineration rotary kiln	182,500	13.0	-	0.9100
2117	Incineration moving grate	711,000	14.0	26.0	0.8980
2118	Incineration fluidized bed	75,000	15.0	-	0.6046
2119	Incineration moving grate	711,000	16.0	28.5	0.8980
2120	Incineration rotary kiln	365,000	20.0	-	0.9100

Appendix A.2. Enterprises' Emissions Indicators

Code	Dust	SO_2	NOx	CO	TOC	HCL	HF	Metals	Hg	PCDD/F	Cd
	Emissions										
-	mg/m^3	mg/m^3	mg/m^3	mg/m^3	mg/m^3	mg/m^3	mg/m^3	mg/m^3	mg/m^3	ng TEQ/m^3	mg/Nm^3
567	0.95	8.00	166.90	10.00	0.00	5.10	0.00	0.03	0.01	0.00	0.01
670	0.13	1.06	133.00	8.01	0.38	0.13	0.00	1.44	0.00	0.00	0.00
678	0.13	0.70	2.50	1.50	0.00	0.13	0.00	1.44	33.02	0.00	0.06
916	0.44	0.40	41.40	5.50	1.87	1.90	0.46	99.22	0.00	0.01	0.00
938	0.33	0.52	104.42	1.77	0.25	3.74	0.14	27.47	0.39	0.00	0.19
1295	6.80	3.30	20.90	6.20	4.00	3.70	0.03	45.00	0.02	0.01	0.14
1876	2.90	9.29	148.86	24.52	0.88	7.54	78.90	13.75	3.86	0.00	0.45
1961	9.10	18.09	2.60	2.10	0.00	3.87	7.40	1.00	0.01	0.00	0.00
1981	35.70	8.70	46.66	11.37	0.20	3.87	7.62	2500.00	76.40	0.00	0.18
2117	8.70	51.00	927.00	51.00	0.96	18.30	0.90	684.00	10.00	0.00	0.01
2118	4.86	49.20	106.00	95.20	1.44	4.85	0.26	289.89	9.55	0.00	0.00
2119	0.00	15.00	850.00	200.00	0.96	10.10	0.68	684.00	10.00	0.00	0.00
2120	1.14	10.11	10.04	0.84	9.70	3.87	7.62	1.00	0.01	0.00	0.00

Appendix A.3. Enterprises' Life Cycle Assessment Indicators

Code	GW	AC	TE	POFh	HTa	HTs	ETs
	LCA						
-	kg CO_2-equivalent	m^2 unprotected ecosystem	m^2 unprotected ecosystem	pers·ppm·hour	m^3 air	m^3 solid	m^3 solid
567	0.0050	−0.0200	−0.0035	−0.0050	−0.0020	0.4000	None
670	−0.0500	−0.0300	−0.0100	−0.0250	−0.0040	0.3500	None
678	0.6250	−0.0300	−0.0100	−0.0250	−0.0040	0.3500	None
916	−0.0100	−0.0220	−0.0070	−0.0100	−0.0030	0.0030	None
938	0.0024	0.0375	0.0375	0.0022	0.0684	0.0108	None
1295	0.0100	−0.0180	−0.0070	−0.0750	−0.0030	0.0250	None
1876	0.0400	−1.0000	−0.0370	−1.0000	−0.0450	−0.0450	None
1961	0.6000	0.2188	−0.0022	0.4520	0.0004	0.1117	0.000
1981	0.1393	0.4386	−0.0013	0.4520	0.0004	0.1117	0.000
2117	0.0020	−0.0070	0.0070	0.0070	0.0020	0.0170	0.000
2118	0.0110	−0.0004	0.0090	0.0150	0.0040	0.0160	0.000
2119	−0.0550	0.0000	−0.0007	0.0003	−0.0097	−0.0097	0.000
2120	−0.0500	−0.0010	−0.0013	0.4520	0.0004	0.1117	0.000

Source: Compiled by the authors.

Appendix B. A Set of Economic Indicators for MSW Heat Treatment Enterprises

Code	Revenue	Expenses	ROI	Diesel_ash	Electricity_ash	Pre-Treatment
-	$	$	%	L/ton	kWh/ton	Boolean
567	23,312,999	19,696,453	18.36%	3.25	1.34	1
670	17,042,511	11,965,864	42.43%	3.28	2.95	1
678	285,115,060	220,217,540	29.47%	0.16	0.42	1
916	11,934,736,600	10,459,041,400	14.11%	1.10	1.24	0
938	5,890,380	4,236,940	39.02%	0.16	0.42	1
1295	48,472,172,162	42,301,654,078	14.59%	0.74	1.15	0
1876	127,750,000	110,250,000	15.87%	0.16	0.42	1
1961	754,715,700	602,775,900	25.21%	0.16	0.42	0
1981	2,257,940	2,171,926	3.96%	11.00	0.42	0
2117	49,433,805	47,156,088	4.83%	5.60	1.30	0
2118	5,123,081	3,534,616	44.94%	2.30	2.40	1
2119	49,433,805	47,156,088	4.83%	0.16	0.42	0
2120	347,728,766	300,000,000	15.91%	0.16	0.42	0

Source: Compiled by the authors.

Appendix C. Integral Indicator of the Thermal Waste-to-Energy Technologies Environmental and Economic Efficiency Calculation Based on BSC

Appendix C.1. Incineration on a Mechanical Moving Grate Technology

Analysis	Analysis Weight	Indicator	Indicator Weight	Value	Assessment
Economic	0.50	ROI	0.40	0.0000	0.000
		Diesel_ash	0.01	0.5099	−0.005
		Electricity_ash	0.01	0.2862	−0.003
		Pre-treatment	0.08	0	0.000
Environmental_Capacity	0.04	Capacity	0.04	1.0000	0.040
Environmental_Efficiency	0.12	EER	0.04	0.1509	0.006
		HER	0.04	0.0000	0.000
		EE_EU	0.04	0.8607	0.034
Environmental_Emissions	0.17	Dust	0.01545	0.1921	−0.003
		SO_2	0.01545	0.4398	−0.007
		NO_x	0.01545	1.0000	−0.015
		CO	0.01545	0.8928	−0.014
		TOC	0.01545	0.2819	−0.004
		HCL	0.01545	1.0000	−0.015
		HF	0.01545	0.0258	0.000
		Metals	0.01545	0.5857	−0.009
		Hg	0.01545	0.2611	−0.004
		PCDD/F	0.01545	0.3333	−0.005
		Cd	0.01545	0.0058	0.000
Environmental_LCA	0.17	GW	0.02429	0.0000	0.000
		AC	0.02429	0.5818	−0.014
		TE	0.02429	0.5134	−0.012
		POFh	0.02429	0.4240	−0.010
		HTa	0.02429	0.0389	−0.001
		HTs	0.02429	0.0000	0.000
		ETs	0.02429	1.0000	−0.024
SUM	1.0		1.0		−0.067

Appendix C.2. Incineration in a Rotary Kiln Technology

Analysis	Analysis Weight	Indicator	Indicator Weight	Value	Assessment
Economic	0.50	ROI	0.40	0.1919	0.077
		Diesel_ash	0.01	1.0000	−0.010
		Electricity_ash	0.01	0.0000	0.000
		Pre-treatment	0.08	0	0.000
Environmental_Capacity	0.04	Capacity	0.04	0.6025	0.024
Environmental_Efficiency	0.12	EER	0.04	0.0000	0.000
		HER	0.04	1.0000	0.040
		EE_EU	0.04	0.8959	0.036
Environmental_Emissions	0.17	Dust	0.01545	1.0000	−0.015
		SO2	0.01545	0.2363	−0.004
		NOx	0.01545	0.0000	0.000
		CO	0.01545	0.0002	0.000
		TOC	0.01545	0.8164	−0.013
		HCL	0.01545	0.3750	−0.006
		HF	0.01545	0.2864	−0.004
		Metals	0.01545	1.0000	−0.015
		Hg	0.01545	1.0000	−0.015
		PCDD/F	0.01545	0.0092	0.000
		Cd	0.01545	0.2714	−0.004
Environmental_LCA	0.17	GW	0.02429	0.8129	−0.020
		AC	0.02429	1.0000	−0.024
		TE	0.02429	0.4424	−0.011
		POFh	0.02429	1.0000	−0.024
		HTa	0.02429	0.3925	−0.010
		HTs	0.02429	0.3124	−0.008
		ETs	0.02429	0.6667	−0.016
SUM	1.0		1.0		−0.023

Appendix C.3. Incineration in a Circulating Fluidized Bed Technology

Analysis	Analysis Weight	Indicator	Indicator Weight	Value	Assessment
Economic	0.50	ROI	0.40	1.0000	0.400
		Diesel_ash	0.01	0.5143	−0.005
		Electricity_ash	0.01	1.0000	−0.010
		Pre-treatment	0.08	1	−0.080
Environmental_Capacity	0.04	Capacity	0.04	0.0000	0.000
Environmental_Efficiency	0.12	EER	0.04	0.0148	0.001
		HER	0.04	-	–
		EE_EU	0.04	0.0000	0.000
Environmental_Emissions	0.17	Dust	0.01545	0.3116	−0.005
		SO_2	0.01545	1.0000	−0.015
		NO_x	0.01545	0.1471	−0.002
		CO	0.01545	1.0000	−0.015
		TOC	0.01545	0.3289	−0.005
		HCL	0.01545	0.4734	−0.007
		HF	0.01545	0.0099	0.000
		Metals	0.01545	0.3465	−0.005
		Hg	0.01545	0.3745	−0.006
		PCDD/F	0.01545	0.0000	0.000
		Cd	0.01545	0.0000	0.000

Analysis	Analysis Weight	Indicator	Indicator Weight	Value	Assessment
Environmental_LCA	0.17	GW	0.02429	0.1037	−0.003
		AC	0.02429	0.5988	−0.015
		TE	0.02429	1.0000	−0.024
		POFh	0.02429	0.4442	−0.011
		HTa	0.02429	0.7186	−0.017
		HTs	0.02429	0.0363	−0.001
		ETs	0.02429	0.0000	0.000
SUM	1.0		1.0		0.174

Appendix C.4. Conventional Gasification Technology

Analysis	Analysis Weight	Indicator	Indicator Weight	Value	Assessment
Economic	0.50	ROI	0.40	0.7571	0.303
		Diesel_ash	0.01	0.3231	−0.003
		Electricity_ash	0.01	0.6389	−0.006
		Pre-treatment	0.08	1	−0.080
Environmental_Capacity	0.04	Capacity	0.04	0.3692	0.015
Environmental_Efficiency	0.12	EER	0.04	1.0000	0.040
		HER	0.04	0.6264	0.025
		EE_EU	0.04	1.0000	0.040
Environmental_Emissions	0.17	Dust	0.01545	0.0000	0.000
		SO_2	0.01545	0.0000	0.000
		NO_x	0.01545	0.0818	−0.001
		CO	0.01545	0.0000	0.000
		TOC	0.01545	0.0000	0.000
		HCL	0.01545	0.0000	0.000
		HF	0.01545	0.0000	0.000
		Metals	0.01545	0.0000	0.000
		Hg	0.01545	0.6478	−0.010
		PCDD/F	0.01545	0.3333	−0.005
		Cd	0.01545	0.1334	−0.002
Environmental_LCA	0.17	GW	0.02429	1.0000	−0.024
		AC	0.02429	0.5446	−0.013
		TE	0.02429	0.0000	0.000
		POFh	0.02429	0.3933	−0.010
		HTa	0.02429	0.0000	0.000
		HTs	0.02429	1.0000	−0.024
		ETs	0.02429	None	None
SUM	1.0		1.0		0.243

Appendix C.5. Plasma Gasification Technology

Analysis	Analysis Weight	Indicator	Indicator Weight	Value	Assessment
Economic	0.50	ROI	0.40	0.1800	0.072
		Diesel_ash	0.01	0.0000	0.000
		Electricity_ash	0.01	0.3687	−0.004
		Pre-treatment	0.08	0	0.000
Environmental_Capacity	0.04	Capacity	0.04	0.2094	0.008
Environmental_Efficiency	0.12	EER	0.04	0.3698	0.022
		HER	0.04	-	–
		EE_EU	0.04	0.0000	0.000

Analysis	Analysis Weight	Indicator	Indicator Weight	Value	Assessment
Environmental_Emissions	0.17	Dust	0.01545	0.4393	−0.007
		SO_2	0.01545	0.0501	−0.001
		NO_x	0.01545	0.0019	0.000
		CO	0.01545	0.0160	0.000
		TOC	0.01545	1.0000	−0.015
		HCL	0.01545	0.3581	−0.006
		HF	0.01545	0.0011	0.000
		Metals	0.01545	0.0523	−0.001
		Hg	0.01545	0.0000	0.000
		PCDD/F	0.01545	1.0000	−0.015
		Cd	0.01545	0.6478	−0.010
Environmental_LCA	0.17	GW	0.02429	0.1005	−0.002
		AC	0.02429	0.5666	−0.014
		TE	0.02429	0.1579	−0.004
		POFh	0.02429	0.3297	−0.008
		HTa	0.02429	0.0898	−0.002
		HTs	0.02429	0.0622	−0.002
		ETs	0.02429	None	None
SUM	1.0		1.0		0.012

Appendix C.6. Pyrolysis Technology

Analysis	Analysis Weight	Indicator	Indicator Weight	Value	Assessment
Economic	0.50	ROI	0.40	0.4456	0.178
		Diesel_ash	0.01	0.1484	−0.001
		Electricity_ash	0.01	0.1549	−0.002
		Pre-treatment	0.08	1	−0.080
Environmental_Capacity	0.04	Capacity	0.04	0.6965	0.028
Environmental_Efficiency	0.12	EER	0.04	0.2367	0.009
		HER	0.04	0.9434	0.038
		EE_EU	0.04	0.5732	0.023
Environmental_Emissions	0.17	Dust	0.01545	0.0832	−0.001
		SO2	0.01545	0.1046	−0.002
		NOx	0.01545	0.2052	−0.003
		CO	0.01545	0.0812	−0.001
		TOC	0.01545	0.0489	−0.001
		HCL	0.01545	0.5347	−0.008
		HF	0.01545	1.0000	−0.015
		Metals	0.01545	0.0148	0.000
		Hg	0.01545	0.0550	−0.001
		PCDD/F	0.01545	0.1664	−0.003
		Cd	0.01545	1.0000	−0.015
Environmental_LCA	0.17	GW	0.02429	0.1193	−0.003
		AC	0.02429	0.0000	0.000
		TE	0.02429	0.4737	−0.012
		POFh	0.02429	0.0000	0.000
		HTa	0.02429	1.0000	−0.024
		HTs	0.02429	0.3419	−0.008
		ETs	0.02429	None	None
SUM	1.0		1.0		0.095

Source: Compiled by the authors.

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