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An optimization-based analysis of waste to energy options for different income level countries

Irem Firtina-Ertis[1] | **Nur Ayvaz-Cavdaroglu**[2] | **Asli Coban**[3]

[1]Faculty of Engineering and Natural Sciences, Energy Systems Engineering Department, Bahçeşehir University, İstanbul, Turkey

[2]Faculty of Management, Business Administration Department, Kadir Has University, İstanbul, Turkey

[3]School of Mechanical and Materials Engineering, University College Dublin, Dublin, Ireland

Correspondence
Irem Firtina-Ertis, Faculty of Engineering and Natural Sciences, Energy Systems Engineering Department, Bahçeşehir University, İstanbul 34353, Turkey.
Email: irem.firtina@eng.bau.edu.tr

Summary

Utilizing waste-to-energy (WtE) technologies is becoming crucial in today's world where energy sources are scarce. Despite the fact that WtE technologies (incineration, gasification, pyrolysis, anaerobic digestion, and landfill gas recovery) have been analyzed thoroughly in the literature regarding their efficiency rates in treating waste, the applicability of each method to different waste compositions and in various economic environments has not been considered before. In this study, this issue is investigated by modeling and solving a mixed integer programming model. The model is illustrated in three settings, namely Turkey, Brazil, and Germany, each of which is an example of a lower middle income, upper middle income, and a high income country, respectively. The findings of the optimization model suggest that plasma-arc gasification and advanced incineration stand out as the most efficient technologies to create the WtE conversion, provided that there are sufficient funds to build and run these facilities. If there are economic restraints, anaerobic digestion could be a more cost-effective way to create energy from waste. However, the solutions can be highly dependent on the parameters of the problem, as indicated in the results of the sensitivity analysis performed. In particular, if CO_2 emissions are a big concern, the optimization model favors more of plasma-arc and pyrolysis technologies.

Novelty Statement

Despite a wide range of previous studies involving technical analysis of WtE technologies, an economic perspective involving facility building decisions comparing different income level countries has not been performed before. This study examines all waste-to-energy methods in the literature not only regarding their efficiency rates in treating waste but also selecting the most appropriate methodology in different settings. In this manner, considering different income level countries brings a proper perspective and novelty to the study.

KEYWORDS

mixed integer programming, municipal solid waste management, optimization, waste-to-energy

1 | INTRODUCTION

Sustainable treatment of municipal solid waste (MSW) is very important in many aspects. In addition to its negative effects on human health and environment, poorly managed MSW could also have a significant impact on vulnerable populations.[1] On the contrary, MSW can be a source of additional income if properly treated. The momentum of technology has reached a tipping point where sustainable MSW treatment processes can turn the people's waste problem into a useful energy source, creating both economic benefits and improving the sustainability of the systems.[2] Waste-to-energy (WtE) facilities that the MSW disposal method provides have two benefits: (a) the reduction in materials to be landfilled and (b) the energy recovery.[3] MSW can be treated in thermal treatment plants to generate energy in different forms (namely electricity and process heat). The primary WtE processes used for energy recovery from MSW are the incineration (direct combustion, INC), the pyrolysis (PYR), the plasma-arc gasification (PLA), and more conventionally, biochemical processes such as the anaerobic digestion (AD), which is used for the biodegradable fraction of MSW.[4-6] It is also possible to create combinations of these processes.

In the INC, the waste is burned in furnaces, and the heat generated is used to produce electricity or heat. Building the INC plants is expensive compared to other conventional solid waste treatment options, and people generally do not want to live in close proximity to these plants because of possible toxic gases (eg, dioxins and furans) released into atmosphere. However, the toxic gas emissions have decreased in recent years due to more stringent rules enforced by governments and the technological advances in this area. The INC technology is used prevalently in several European countries (namely France, Germany, the United Kingdom, Italy, and Sweden). The volume of waste treated in landfills can be reduced by up to 90% with the INC. In the European Union (EU) countries, 30% of waste is processed to generate energy according to 2017 figures.[7]

The PYR is another process where organic fraction of the waste is decomposed by heat (400°C-1000°C) in the absence of an oxidizing agent. The WtE potential of the PYR is similar to gasification. However, these methods are less mature compared to the AD and the INC.[8]

The PLA is a new technology for MSW treatment with several advantages compared to conventional forms of gasification and the INC in particular.[3] The main advantage of this system is that it reaches high temperatures compared to conventional systems and has higher efficiency and lower emissions.[3,9] The main disadvantage of the process is that it requires a large amount of electrical energy input, which increases cost.

In the AD process, biodegradable materials are decomposed by bacteria under anaerobic conditions, which lead to biogas production, a source of renewable energy consisting of methane and carbon dioxide. The principal advantages of the AD are its lower carbon dioxide and odor emissions and improved organic matter valorization. The main disadvantage is that the process is slow, so using only the AD processes to remove all the waste may not be practical. A total of 90% of these AD plants are located in Europe, Germany, France, Italy, and Poland which have the biggest biogas markets.[8]

All WtE methods stated above have been analyzed thoroughly in the past regarding their efficiency rates in treating waste.[10-12] However, to our knowledge, selecting the most appropriate technology in different settings with varying socioeconomic conditions is not researched extensively. In this study, this issue is investigated by modeling and solving a mixed integer programming (MIP) model. The model is illustrated in three settings, namely Turkey, Brazil, and Germany, each of which is an example of a lower middle income (LMI), upper middle income (UMI), and high income (HI) country, respectively. The reason for selecting these three countries is because they are good representatives of the LMI, UMI, and HI groups of diverse countries.

Using mathematical programming models, particularly MIP models, in MSW management, is not a new approach.[13] In the literature, several case studies are presented showing the efficacy of the solution generated by using mathematical tools. For example, Benítez et al[14] develop mathematical models that correlate MSW generation per capita with education, household income, and population. Similar studies cover different regions of the world, like, for example, Port Said-Egypt,[15] Alleghany County-United States,[16] Foshan-China,[17,18] Beijing-China,[19] Hong Kong,[20] Brazil,[21] and Italy.[22] Most of these papers contain formulations of MIP.

WtE technologies and their application to treat MSW have been considered in the literature before.[4,23-25] Kumar and Samadder[26] present a review of several WtE technologies and provide an assessment of various options for different income level countries. Mohammadi and Harjunskonski[27] propose a theoretical MIP model that aims to maximize the generation of fuel and energy from MSW. They evaluate various WtE technologies both on their economic and environmental impacts. Potential and cost of electricity generation from MSW have been considered in many studies, tailored to different countries.[28-34] However, most of these studies limit their analyses on a particular region and usually do not use optimization algorithms. Rizwan et al's[25] work involves a multiobjective optimization model for sustainable MSW processing; however, their model is only applied on a single-country case study. Leme et al[9] carry out technoeconomic and environmental impact analysis of energy recovery from MSW in Brazil. They develop hypothetical scenarios according to different numbers of inhabitants living in an urban area and find that population is an important factor in determining biogas generation from landfills while the WtE facility option is not economically feasible for all the scenarios. Fernández-González et al[35] perform an analysis about the economic and environmental costs of various WtE technologies for 13 municipalities from southern Spain. They find that, from an economic standpoint, gasification presents the lowest value and from an environmental aspect, the INC has significant advantages over the current practice in the country. Perrot and Subiantoro[8] discuss MSW management and WtE potentials in New Zealand. Four options for WtE technology, that is, the INC, the AD, gasification, and the PYR are compared based on air pollution, cost, by-products, capacity, commercial maturity, energy efficiency, and type of waste treated. It is found that the AD tends to be the country's most appealing approach from environmental and economic aspects. Again, although these works involve mathematical modeling, their results are confined to a single region, and they do not compare the suitability of different technologies across various regions. In a similar fashion, some studies use optimization methodologies to evaluate efficiency of a single/only a few WtE technologies. For instance, Zhang et al[36] use an optimization model to determine the optimal mixing strategy of organic waste in order to render the most efficient AD system. Another study favoring the AD is performed by Tan et al[37] where a comparison of various WtE options and further discussion on the INC and the AD are presented for Malaysia. They state that incinerators could deliver the best results by means of electricity and heat production from an economic and environmental aspect; however, if heat production is not included, the AD appears to be the most sustainable option. Malinauskaite et al[38] suggest a comprehensive evaluation of MSW management systems and WtE options related to the circular economy in different European countries. Lino and Ismail[39] propose two scenarios (ie, the INC, bio-digestion, and recycling) for a Brazilian city to treat waste with energy recovery.

Despite the broad span of studies focusing on different aspects of WtE technologies and the widespread utilization of optimization techniques in the topic, to our knowledge, there does not exist a mathematical model toward determining the optimal strategy for the combination of WtE technologies to be applied on a country scale. Furthermore, comparing and contrasting the appropriate strategies for countries of different income levels have not been performed before.

Another contribution of our study is to evaluate WtE technologies in the context of circular economy. In contrast to the traditional (noncircular) economy, the circular economy is based on the concept of zero waste, so that the resource is converted into value-added products and used in a sustainable manner being more environmentally friendly.[40] Circular economy alternatives can provide better management of waste and bring environmental benefits such as producing cleaner energy, increasing energy efficiency, and avoiding costs (even generate profits). With the advancement of the circular economy and closing loops, new methods for generating energy from waste have been becoming more prominent. Circular economy practices can offer opportunities for reducing GHG emissions in the waste to energy sector through the circulation of waste materials.[40,41]

Therefore, the objective of this work is to be able to present the best combinations of WtE technologies to be used, given the waste composition and economic conditions of different countries and evaluate the benefits of WtE technologies in a circular economy context. Furthermore, presenting a sensitivity analysis regarding how proposed solutions vary with changing values of parameters and also providing different solutions subject to further limitations on gas emissions is another contribution of this study, which is a novelty on the existing literature.

2 | MODELING FRAMEWORK

2.1 | Problem statement

In this article, it is inquired which options of converting WtE are more appropriate to be applied in various countries with different income levels and different waste compositions. Toward this end, an optimization problem is developed that aims to establish the most cost-effective plan of utilizing various thermochemical and biochemical energy facilities to generate energy from waste in each setting.

The objective function of the optimization problem is selected to maximize the net profit, which is defined as the difference between the revenue and total cost (operation and maintenance [O&M] and capital cost). The decision variables are the numbers of various thermal energy plants to be maintained. The constraints involve the funds available for MSW and the amount of waste to be processed every day. An additional constraint regarding the amount of CO_2 emissions is added in the model in the sensitivity analysis section. The model will be explained in further detail in the model formulation section (Section 2.5).

2.2 | Background information

The optimization model is developed based on the information on different MSW treatment technologies. MSW treatment includes various processing stages (eg, segregation MSW into various components and converting MSW into energy). In general, mixed MSW includes several components namely food waste, paper, plastic, wood waste, glass, metal, textile, etc.[42]

In this study, it is assumed that MSW treatment begins with the segregation of MSW into its components. Then, all the glasses and metals are supposed to be removed from the MSW beforehand and used for recycling. All the other constituents which are organic, paper, and plastic are used for energy production via different methods. In practice, the segregation phase could be a very complicated and costly process on its own. The methods used in segregation vary from country to country, even among the cities of the same country or among waste treatment facilities. Therefore, we assume the segregation step is already performed where it is necessary for the respective process (eg, AD), and instead the focus of this study is on the energy potential of the waste components across different recovery methods. Furthermore, it should be noted that energy recovery by means of heat is ignored in this study, and only the electricity-based energy recovery is considered. The focus is on the energy recovery from MSW by using thermochemical and biochemical conversion technologies, as these types of MSW treatment can be more advantageous in terms of energy efficiency and sustainability than landfill disposal.

The optimization model is developed to determine the optimal processing pathway for thermochemical/biochemical conversion of MSW (which is already segregated) into energy for countries at different income levels. The model is applied to the cases of Turkey, Brazil, and Germany, which are selected as examples to LMI, UMI, and HI countries, respectively. The typical waste composition of MSW is given for different income level countries in Table 1.

Table 2 states additional information regarding the population, amount of waste generation per day, and the collected waste amount in the three countries selected. Note that the populations of Turkey and Germany are comparable to each other, the collection coverage percentages of Turkey and Brazil are similar, and total collected MSW per day value of Germany and Brazil are alike.

The potential alternatives integrated in the MSW model for processing and converting MSW into energy are the AD, the PLA, the PYR, the conventional INC, and the ADV INC followed by electricity generation. The ADV INC term corresponds to the concept of WtE and gas turbine integrated power incineration systems in this study. These systems are more efficient than the conventional systems since they operate on a hybrid combined cycle, a thermal connection between a topping cycle and a bottomer cycle.[45] Landfill-based electricity generation is not included in this study since the amount of electricity generated by landfill is considerable over large timeframes. It is also not possible to treat some of the waste components via certain methods, for example, the AD can only be applicable on organic waste, glass and metal cannot be processed via the PYR or the PLA, etc.

The objective is to determine the optimal processing pathway for the thermochemical/biochemical conversion of MSW into energy. A series of chemical and physical waste characterization experiments must be performed, primarily proximate, and ultimate analysis, in order to understand the state of MSW and its energy potential. The details of these processes are explained in the next subsection.

2.3 | Energy potential estimation method

This section provides the technology used to measure the electrical energy potential of MSW. The two fundamental

Component (wt%)	Turkey (LMI)	Brazil (UMI)	Germany (Europe) (HI)
Organic (food waste)	59	54	25
Paper	10	15	30
Plastic	13	12	11
Metals	2	3	6
Glass	4	4	7
Others	12	12	21

TABLE 1 The typical waste composition of municipal solid waste for different income level countries[43]

TABLE 2 Population and waste specifications of three countries with different income levels[43,44]

	Turkey (LMI)	Brazil (UMI)	Germany (Europe) (HI)
Population (Million)-2019	81	209	83
Waste per capita (kg/capita/day)	1.77	1.03	2.11
Collection coverage (%)	77	83	100
Total generation (ton/year)	51 684 000	78 573 550	63 922 450
Total collected municipal solid waste (ton/year)	39 796 680	65 216 047	63 922 450
Food waste (ton/year)	23 480 041	35 216 665	17 898 286
Paper (ton/year)	3 581 701	9 130 247	19 815 960
Plastic (ton/year)	4 775 602	7 173 765	7 031 470
Amount of waste generated (ton/day)	141 600	215 270	175 130
Amount of waste collected (ton/day)	109 032	178 674	175 130

TABLE 3 Ultimate analysis of municipal solid waste streams as mass percentages (wt%)[33,46]

Components	C%	H%	O%	N%	S%
Organic	48.0	6.4	37.6	2.6	0.4
Paper	43.5	6	44	0.3	0.2
Plastic	60	7.2	22.8	—	—

methods used are the ultimate analysis and the proximate analysis.

The ultimate analysis is used to determine the chemical composition of MSW.[46] The ultimate analysis of different waste streams as a percentage of total mass is presented in Table 3, which was stated in Niessen,[46] apart from a second study reported in Themelis et al.[33]

On the other hand, the proximate analysis is used to determine the moisture, fixed organic matter, volatile organic matter, and ash content of MSW. However, in this study, the moisture content is only given in Table 4 and used for dry-stream calculations.[33,46] The proximate analysis results of MSW for different countries are not going to be totally the same as MSW is a heterogeneous resource, but the results of review studies mentioned in the literature found only slight variations.[33,46]

The electrical energy potential of MSW is calculated by considering five transformation alternatives namely the INC (conventional), the PYR, the PLA, the AD, and the ADV INC. The quantity and composition of MSW depend on socioeconomic and cultural factors. For example, in rural areas, the organic content of MSW is lower, while in urban areas, it is higher. Moreover, the quantity and composition differ based on the income level of countries. Note that the waste compositions and amounts of the three countries on which the model will be applied are already presented in Tables 1 and 2.

The heat generated as a result of thermal conversion is referred to as the heating value. There are two methods to present the heating value of a substance, namely the higher heating value (HHV) and the lower heating value (LHV). The post-processing method of the produced steam determines the selection of HHV or LHV. Condensing the steam results in a higher energy release, and the heating value is called the HHV. If condensing the steam is not the case, the heating value does not account for the extra energy released from the steam condensation, and so the heating value is called the LHV. Using the HHV value in the design process is more suitable when advanced combustion units having secondary or tertiary condensers are designed. In this study, the HHV value is calculated by using the following equation[47,48]:

$$\begin{aligned}\mathrm{HHV}\,(\mathrm{MJ/ton}) = (0.3491\times \mathrm{C}\%) + (1.1783\times \mathrm{H}\%)\\ -(0.1043\times \mathrm{O}\%),\end{aligned} \tag{1}$$

where C%, H%, and O% represent the carbon, hydrogen, and oxygen mass percentages of the waste stream, respectively.

In this analysis, first, the HHV values of the MSW components are calculated using Equation (1). The theoretical maximum energy values are represented in Table 4. The actual net energy, which can be derived from different thermochemical (ie, the INC, the PYR, and the PLA) and biochemical (ie, the AD) energy conversion methods, is based on the use of energy (electricity) and the performance of the energy cycles used. For instance, conventional electricity-only incinerators have a lumped efficiency of around 21%, which also considers the energy utilized in the incineration process itself.

Using the efficiency values for different conversion methods, the efficiency-adjusted HHV values are presented in Table 5 to represent the electricity production projection from different methods for different income level countries. As stated in Table 4, different MSW components have various wet and dry bases heating values. Plastic has the highest heating value, while organic waste has the lowest. The applicability of thermal conversion methods to all the waste streams (except for metal and glass) is advantageous. If the waste composition is known in terms of the wet weight, moisture content must be subtracted from the composition fractions.[49]

The electricity generation potential via the thermal energy conversion methods as the INC, the PYR, the PLA, and the ADV INC, all the MSW generated in different income level countries is estimated by using the following equation:

$$HHV_{MSW} \times \eta_e = E_{INC}, \tag{2}$$

where HHV_{MSW} is the HHV of the MSW, and η_e, the efficiency of electrical energy conversion. HHV_{MSW} is estimated using the average composition of MSW (Table 1) and the HHVs of different types of residues (Table 3), for example, 6113 MJ/ton for organic matter, 15 900 MJ/ton for paper, 27 000 MJ/ton for plastics, and 0 MJ/ton for glass, metals, and others. Obviously, sending glass or metal to an incineration or gasification facility does not make sense, so these components in the facility must remain unprocessed. The resulting value of HHV_{MSW} is 8277 MJ/ton for Turkey, 8497 MJ/ton for Brazil, and 9610 MJ/ton for Germany as LMI, UMI, and HI countries, respectively. Finally, a value of η_e is 21%, corresponding to the conventional INC and 42% for the ADV INC are assumed. Similarly, η_e is 20.5% for the PYR, but the PLA is the advanced method for gasification in accordance with η_e is 35% (shown in Table 4). Considering the thermodynamic cycle used, the size of the plant, and all the methods used for optimization (that are

TABLE 4 The efficiency-adjusted higher heating values (HHVs) to reflect the prediction of electricity generation from different methods for each municipal solid waste stream

	Moisture content[b]		HHV	Efficiency-adjusted electrical energy output[a]									
				INC (21%)		PLA (35%)		PYR (20.5%)		AD (10.4%)		ADV INC (42%)	
Unit	wt %	MJ/kg[c]	MJ/ton or kJ/kg[d]	MJ/ton	kWh/ton[e]	MJ/ton	kWh/ton[e]	MJ/ton	kWh/ton[e]	MJ/ton	kWh/ton[e]	MJ/ton	kWh/ton[e]
Organic	70	20.38	6113	1284	359	2140	599	1253	351	636	178	2567	719
Paper	10.2	17.67	15 900	3339	935	5565	1558	3259	913	—	—	6678	1870
Plastic	0.2	27.05	27 000	5670	1587	9449	2646	5535	1550	—	—	11 339	3175

[a] Inner parenthesis values represent the electrical efficiencies of the methods.[8]

[b] Themelis et al[33] and Niessen.[46]

[c] Wet basis (calculated based on Reference 47).

[d] Dry basis.

[e] Unit conversion (MJ to kWh).

TABLE 5 Electricity production projection with different methods for different income level countries

	HHV (dry basis)	Electrical energy output									
		INC		PLA		PYR		AD		ADV INC	
Unit	kJ/kg	MJ/ton	kWh/ton	MJ/ton	kWh/ton	MJ/ton	kWh/ton	MJ/ton	kWh/ton	MJ/ton	kWh/ton
Turkey (LMI)	8277	1738	487	2897	811	1697	475	656	184	3476	973
Brazil (UMI)	8497	1784	500	2974	833	1742	488	601	168	3569	999
Germany (HI)	9610	2018	565	3364	942	1970	552	311	87	4036	1130

different for each plant), the efficiency of each technology is different.[8]

The electricity production potential of the AD for whole organic fraction of MSW (O_{MSW}) generated in different income level countries is estimated as:

$$E_{AD} = M_{O_{MSW}} \times f \times LHV_{CH4} \times \eta_e, \qquad (3)$$

where f is the organic matter fraction of MSW and $M_{O_{MSW}}$ is the methane generation rate per ton of O_{MSW} (Nm^3/ton). Although the AD is performed under controlled operating conditions, the literature records different methane generation amounts from O_{MSW}, ranging from 67.5 to 122 Nm^3/ton O_{MSW}.[35] In this study, a value of 115 Nm^3/ton has been applied. The value of η_e has been applied as 0.26; this value is less than the stated efficiency of the reciprocating internal combustion engine as it is the net electrical energy requirement for internal consumption of the plant. LHV of methane (LHV_{CH4}) is taken as 37.2 MJ/Nm^3. The value of E_{AD} is 656 MJ/ton for Turkey, 601 MJ/ton for Brazil, and 311 MJ/ton for Germany as the representation of LMI, UMI, and HI countries, respectively.[8]

2.4 | Economic evaluation

The capital investment costs of different WtE technologies are generally high, but the costs may vary based on the technology used and the size of the facility. Gasification technologies generally require more capital investment than traditional combustion technologies. For instance, a gasification plant in the USA with a capacity of 750 tons/year would approximately require a funding amount of \$550 per annual capacity ton.[50] Even the investment costs for the same technology and similar facility may differ considerably based on the precise location selected and site restrictions. For instance, two conventional (grate) combustion WtE facilities located in different cities of China are compared, and they represent a major discrepancy in terms of the embarked capital as an example. The WtE plant in the city of Foshan, with a capacity of 462 000 tons/year, requires an investment cost of \$120 per annual capacity ton, whereas the plant in Shanghai, with a capacity of 495 000 tons per year, requires \$282 per annual capacity ton.[17] WtE facilities in developing countries are apt to have a lower investment cost although the same Western technology is utilized.

There are local variations in government motivations and market dynamics, and the revenue amount obtained is strongly connected with local parameters such as electricity prices and the marketable values of the recyclables (ie, metals, paper, glass, plastic). Therefore, it is not easy to generalize investment costs for each technology. Moreover, investment costs of individual projects will hinge on different parameters such as the financing type, project developer, financial market conditions, maturity of technology, and risk and political factors.[50]

The capacity of production, regarding the waste treatment facilities, clearly hinges on the treatment facility size. However, there are some figures that may act as reference points by considering the performances of the existing plants in different countries. The common scales of capacity of each technology are as follows: (a) the INC can treat

TABLE 6 Estimated cost values of different WtE facilities according to the income levels (Adapted from References 6,51,and 52)

HI	**INC**		**PYR**		**PLA**		**AD**		**ADV INC**	
Plant capacity (ton/day)	500	1000	500	1000	500	1000	137	274	500	1000
Capital cost (\$/ton)	636	489	562	432	557	428	400	308	900	692
O&M (\$/ton)	45	35	42	33	41	32	30	23	58	45
Total cost (M\$)	116	178	103	158	102	156	20	31	164	253
UMI	**INC**		**PYR**		**PLA**		**AD**		**ADV INC**	
Plant capacity (ton/day)	500	1000	500	1000	500	1000	137	274	500	1000
Capital cost (\$/ton)	400	308	375	288	371	285	325	250	600	462
O&M (\$/ton)	29	22	29	22	28	22	25	19	38	29
Total cost (M\$)	73	112	68	105	68	104	16	25	109	168
LMI	**INC**		**PYR**		**PLA**		**AD**		**ADV INC**	
Plant capacity (ton/day)	500	1000	500	1000	500	1000	137	274	500	1000
Capital cost (\$/ton)	300	231	288	222	285	219	267	205	390	300
O&M (\$/ton)	21	16	22	17	22	17	17	13	27	21
Total cost (M\$)	55	84	53	81	52	80	13	21	71	109

1500 tons of waste per day, (b) the PYR and the PLA can treat 100 and 1000 tons of waste per day, respectively, and (c) the AD can treat around 500 tons of waste per day.[8]

In alignment with the above discussion, two levels of each treatment facility are involved in this model, that is, large (1000 ton/day) and small (500 ton/day). Although, in general, the unit operating costs and the unit capital costs decrease with the size of the facility, these costs do not change at a linear scale. Therefore, it is not possible to incorporate all different capacities. Hence, we restrict our attention to two sizes of each facility. The cost parameters regarding each size of the plants at each income level are given in Table 6. These parameters are estimated by adapting the data represented in the related references in the literature.[6,51,52]

Regarding the revenue computation, the WtE potential of each waste component is computed considering the HHV computations stated in Table 4. These values and the unit prices of electricity in each country are stated in Table 7.[53] In addition to these revenues, there are also 'tipping fees' (gate fee), which correspond to the fees charged by the owner or operator of a landfill or other waste disposal facilities for the acceptance of a unit weight or volume of solid waste for disposal. These are ignored in our computations, since they apply to all the methods discussed evenly.

2.5 | Formulation of the MIP model

The MIP model that estimates the number of waste management facilities required in the most cost-effective manner is formulated as follows:

$$Min\ TC = \sum_{j=1}^{10}\sum_{i=1}^{3} C_j P_{ij} - \sum_{j=1}^{10}\sum_{i=1}^{3} R_{ij} P_{ij}. \tag{4}$$

Subject to:

$$P_{i=}\sum_{j} P_{ij}, \forall i = 1,2,3, \tag{5}$$

$$\sum_{i} P_{ij} \le X_j Cap_j, j = 1,2...10, \tag{6}$$

$$\sum_{j=1}^{10} CC_j X_j \le TF, \tag{7}$$

$$P_{ij} \ge 0, \forall i, j, X_j integer, \tag{8}$$

where:

TC : total cost of utilizing waste components for energy production.

TABLE 7 Estimated revenues by electrical energy output per ton of waste based on income levels

HI countries ($/ton)					
	INC	**PLA**	**PYR**	**AD**	**ADV INC**
Organic	129	216	126	64	259
Paper	337	561	329	—	673
Plastic	571	952	558	—	1143
Electricity price ($/KWh)	0.36				
UMI countries ($/ton)					
	INC	**PLA**	**PYR**	**AD**	**ADV INC**
Organic	68	114	67	12	137
Paper	178	296	173	—	355
Plastic	302	503	294	—	603
Electricity price ($/KWh)	0.19				
LMI countries ($/ton)					
	INC	**PLA**	**PYR**	**AD**	**ADV INC**
Organic	40	66	39	20	79
Paper	103	171	100	—	206
Plastic	175	291	170	—	349
Electricity price ($/KWh)	0.11				

C_j : maintenance/operating cost for facility j (per ton), ($j = 1$ small INC, $j = 2$ small PYR, $j = 3$ small PLA, $j = 4$ small AD, $j = 5$ small ADV INC, $j = 6$ large INC, $j = 7$ large PYR, $j = 8$ large PLA, $j = 9$ large AD, $j = 10$ large ADV INC).

CC_j : capital cost for facility j (per year), ($j = 1$ small INC, ..., $j = 10$ large ADV INC).

R_{ij} : revenue correspondence of the energy produced in facility j by treating component i (per ton), ($j = 1$ small INC, ..., $j = 10$ large ADV INC; $i = 1$ paper, $i = 2$ organic, $i = 3$ plastic).

TF: total funds available for building and operating MSW facilities to convert WtE (per year) (differs across countries with different income levels).

P_i : the rate at which waste component i accumulates per day, ($i = 1$ paper, $i = 2$ organic, $i = 3$ plastic).

P_{ij} : amount of waste component i that is sent to facility j per day, ($j = 1$ small INC, ..., $j = 10$ large ADV INC).

X_j : the number of facilities j to be built and operated ($j = 1$ small INC, ..., $j = 10$ large ADV INC).

Cap_j : Capacity of facility j ($j = 1$ small INC, ..., $j = 10$ large ADV INC).

In the optimization problem defined above, one primarily intends to compute the optimum number of treatment facilities to build and operate in order to minimize the total cost of waste components utilized for energy production. The first term in the objective function Equation (4) calculates the total operating cost of the treatment facilities (which is based on the amount of waste sent to each plant). The next term represents the total economic value of electricity generation related to each component that is treated in each facility. Coming to the constraints, the first constraint (5) makes sure that all waste components are treated in one of the facilities. The second constraint, that is, inequality (6) guarantees that a waste component is only treated in a facility if the total capacity of that facility is sufficient. The next constraint (7) limits the number of facilities that can be built according to the funds available. Finally, inequality (8) indicates that waste amounts sent to each facility need to be nonnegative.

After the optimization problem is solved, a sensitivity analysis is performed using MS Excel Solver Sensitivity Analysis Report. The allowable increase/decrease ranges, the shadow prices of the constraints and the reduced cost values of the objective function coefficients provide us with sufficient information regarding the robustness of the solution and the range of parameter values for which the solution will still be valid. Furthermore, in the sensitivity analysis, the CO_2 emissions of the proposed solutions are calculated, and a new constraint is added to reduce these emissions by 10% and 20%.

In the next section, this model is implemented in order to solve the WtE problem of the three countries, and the results are presented.

3 | RESULTS AND DISCUSSION

3.1 | Results of the optimization model

The MIP model is solved with respect to the cost and revenue parameters tailored to the examples of LMI, UMI, and HI countries, namely in the cases of Turkey, Brazil, and Germany. It is assumed in all three cases that the funds available for building and operating WtE MSW facilities were approximately equivalent to 5%[1] of the

TABLE 8 The number of facilities favored with respect to sizes (small and large) for different income level countries according to the MIP model solution

	Small					Large							
Countries	INC	PYR	PLA	AD	ADV INC	INC	PYR	PLA	AD	ADV INC	Organic	Paper	Plastic
Turkey	0	0	0	0	0	0	0	0	0	49	100% is sent to ADV INC	100% is sent to ADV INC	100% is sent to ADV INC
Brazil	0	0	0	0	1	0	0	97	2	0	0.1% sent to ADV INC, 99.9% is sent to PLA	100% is sent to PLA	96.3% is sent to PLA, 3.7% sent to ADV INC
Germany	0	0	0	0	0	0	0	48	0	43	100% is sent to PLA	28.6% is sent to PLA, 71.4% sent to ADV INC	100% is sent to ADV INC

total funds allocated for MSW management in that country, which is assumed to be roughly 0.5%[54] of the GNP (Gross National Product). Moreover, it is assumed that all facilities are operative for 20 years on average, and the capital costs are calculated accordingly. The results of the optimization model are tabulated in Table 8.

In all three cases, it is observed that the model favors building of the PLA and the ADV INC facilities. In the Turkish case, 49 large-sized ADV INC plants are advocated to be built, while in Germany, 48 large-sized PLA facilities are built in addition to 43 large-capacity ADV INC plants. The Brazilian case is a bit more interesting, where two large-sized AD plants are advocated to be built to treat a small portion of organic waste. Moreover, only large PLA facilities are recommended to be built and one small ADV INC plant.

Obtaining this form of a solution is understandable by analyzing Tables 6 and 7 in detail. In general, the O&M cost and capital cost for the PLA facilities are compatible with the PYR facilities and lower than incineration facilities. Moreover, the unit revenues obtained on all waste types by treating them via the PLA technology are higher than all the other three techniques. Similarly, although the ADV INC facilities are costly to build and run, their efficiency level makes it feasible to obtain larger revenues that compensate the costs. Hence, the model advocates allocating funds to the PLA and the ADV INC facilities. These results are in alignment with the findings of literature; for instance, Mohammadi and Harjunkoski[27] find that the INC technology is the most desirable among five WtE technologies in terms of having the highest net present value and the lowest payback period.

3.2 | Results of the sensitivity analysis

Since the results can be quite parameter-dependent, we also wanted to check the robustness of the solutions by conducting a sensitivity analysis. The findings in this analysis are noted below.

For the INC facilities to be feasible to build, their efficiency rate in electricity generation must be significantly improved to values that are double the size of the current efficiency levels. This is immediately evident in the revenue comparison of the INC vs the ADV INC, and the sensitivity analysis confirms this observation by letting the model build the INC facilities if the revenues obtained from the three waste components in the INC are doubled. However, note that this analysis does not take into account the economic value of the heat produced in these facilities. If an INC facility provides households with large amounts of heat for district heating or industry directly for process needs (heat or steam), the overall efficiency (heat and power) can be sufficiently feasible to build these facilities.

Similarly, the revenue obtained from treating organic waste in the PYR facilities needs to be improved by about 90% in LMI (ie, amounting to $75 per ton) and about 75% in UMI and HI ($117 per ton in UMI and $220 in HI) for their construction to be feasible. A similar increase in the efficiency of treating paper (ie, revenue rates becoming $203, $302, $564 per ton in LMI, UMI, and HI, respectively) or treating plastic (ie, revenue rates becoming $346, $508, $1035 per ton in LMI, UMI, and HI, respectively) will be sufficient for recommending to build these facilities, too. These improvements help bring the efficiency of the PYR roughly to the level of the PLA technology in UMI and HI and to the level of the ADV INC in LMI.

Finally, the revenue obtained from treating organic waste in the AD needs to be more than tripled in size (amounting to $71 per ton in LMI) and more than doubled (at least $163 in HI) for this facility to be favored by the model.

The amount of funds allocated to the building and operating these facilities has certain effects on the obtained solution, too. In the case of Turkey, since the amount of waste to be collected for treatment is low, the model operates by using only about 25% of the funds projected. However, if the funds were decreased below this level, there is no feasible solution to treat all the collected waste. If the problem is resolved by changing the first constraint and making it an inequality ($\leq$) instead of equality, the model opens a fewer number of the ADV INC facilities and leaves part of the organic waste untreated. For the other two instances (LMI and HI cases), all the projected funds are used in the optimal solution. So, we decided to see the effect of having less funds. For instance, if the funds were 5% lower than the amount predicted, the model advocates for opening a fewer number (65) of large PLA facilities and a greater number (119) of large AD facilities in Brazil and treats about 50% of organic waste in the AD. However, this decreases the profitability of the model by about 12%. A 10% cut in the funds results in an even more radical solution, building 1 small and 261 large AD facilities and treating all organic waste in them. The model now builds only 26 large PLA facilities, and the profits are only 62% of the initial case. In Germany, if the funds are restricted to the 95% of the originally projected value, the model advocates to build 57 large PLA and 32 large ADV INC facilities, favoring the PLA further. More interestingly, now four small-sized INC facilities are built in addition, which are used to treat 5% of the organic waste. The profits are 97% of the initial value. When the funds become 90% of initial values projected, 67 large PLA and 24 large ADV INC facilities are built, and the total profits drop to 95% of their original values. Finally, if the funds are cut by 20%, the problem is still feasible and the optimal solution is found by building 1 large INC, 83 large PLA, 9 large AD, and 5 large ADV INC facilities. The INC facility is used to treat some plastic waste while the AD is devoted to organic waste only. The profits decreased by 11% in this instance. Hence, although there seems to be no clear pattern in this analysis, it can be concluded that the AD and the INC are only favored if the funds do not allow to build and run more expensive but more efficient options, the ADV INC and the PLA.

Furthermore, we would like to see how the solutions change if the resulting CO_2 emissions of the proposed solutions are desired to be reduced by 10% and by 20%. To this end, a new constraint computing the CO_2 emissions of the proposed alternatives is added to the model as follows:

$$\sum_{j=1}^{10} CO2_j X_j \leq TE, \tag{9}$$

where TE: limitation on the desired CO_2 emission level (which is first restricted to 10%, then to 20% less than the CO_2 emission level produced by the initial optimal solution in each country).

X_j : the number of facilities j to be built and operated ($j = 1$ small INC, …, $j = 10$ large ADV INC).

$CO2_j$: average CO_2 emissions as a result of the WtE process in facility j (per ton), $j = 1$ small INC, …, $j = 10$ large ADV INC).

The values of $CO2_j$ (kg CO_2/kWh) were estimated according to Murphy and McKeogh.[51] The CO_2 emissions (in kg CO_2/ton MSW) of different WtE technologies were calculated using the energy values (kWh/ton) represented in Table 5. These values are presented in Table 9.

In this study, CO_2 emissions caused by AD process were considered originating from the conversion of methane to CO_2 by the combustion process. The results of the analysis with the new constraint (9) are presented in Table 10.

Table 10 presents interesting results: In the case of Turkey, the emphasis shifts to opening more PLA plants to reduce the current CO_2 emissions. In the case of Brazil, on the other hand, the PYR technology becomes more favored by the model. That is because, in the original solution, Brazil is already supposed to use the PLA technology to treat almost all of MSW, and the only way to reduce carbon emissions is to shift to a more environmentally friendly method, which is the PYR. However, this shift significantly reduces the profitability levels of the Brazilian solution. Finally, again the PLA becomes more favored by the model in the Germany case, since utilizing these plants reduces the carbon emissions compared to the ADV INC without diminishing the profitability too much. Again, these results are supported by the previous findings of literature, too. For instance, Silva-Martínez et al[32] find that gasification technologies

TABLE 9 The CO_2 emissions of different WtE technologies (in kg CO_2/ton municipal solid waste)

	INC	PLA	PYR	AD	ADV INC
Turkey	107.07	93.29	54.64	36.38	214.15
Brazil	57.45	95.76	56.09	33.30	219.83
Germany	111.89	108.31	63.44	17.27	248.64

TABLE 10 The number of facilities favored for different income level countries at normal and reduced CO_2 levels

	Small					Large						
Countries	INC	PYR	PLA	AD	ADV INC	INC	PYR	PLA	AD	ADV INC	CO_2 (t/day)	Profit reduction
Turkey—optimal solution	0	0	0	0	0	0	0	0	0	49	10 444	—
10% CO_2 reduction	0	0	17	0	0	0	0	0	0	40	9399	1%
20% CO_2 reduction	0	0	35	0	0	0	0	0	0	31	8355	2%
Brazil—optimal solution	0	0	0	0	1	0	0	97	2	0	9417	—
10% CO_2 reduction	0	1	0	2	0	1	19	76	4	0	8475	6%
20% CO_2 reduction	0	0	0	0	0	1	44	52	1	0	7514	13%
Germany—optimal solution	0	0	0	0	0	0	0	48	0	43	15 891	—
10% CO_2 reduction	0	0	1	0	1	0	0	59	0	31	14 276	2.5%
20% CO_2 reduction	0	0	0	0	0	0	1	70	0	20	12 618	5%

are the most promising technologies in view of the combined economic and environmental advantages they offer.

All said, one should note that the proposed combination of WtE technologies would still reduce the CO_2 emissions produced by the current MSW-processing practices used in all three countries. This is because currently, landfill method still constitutes a considerable proportion of MSW treatment practice in all countries, and the CO_2 emissions produced by landfilling is much higher compared to the WtE technologies. Therefore, even the original solutions proposed by the MIP model constitute a considerable improvement on the current levels of GHG emissions by reducing the landfilled waste and should be acknowledged as a means of improving sustainability in addition to their economic advantages.

4 | CONCLUSION

This article analyzes the applicability of various WtE methods to different waste compositions in various economic environments. This issue is investigated by modeling and solving an MIP model and illustrating the results in three settings, namely Turkey (LMI), Brazil (UMI), and Germany (HI). Although these three countries are selected as examples, the analysis is applicable to any country provided that appropriate parameters are specified. The attention is on the energy recovery from MSW by using thermochemical and biochemical conversion technologies since these forms of MSW treatment have more economic and environmental advantages than the landfill disposal. As the limitation on landfill disposal sites is a growing issue, these technologies present both economically and environmentally more advantageous solutions, by yielding a reduction of waste of 70% in mass and of 80% to 90% in volume and also by reduction of GHG in comparison with landfilling.[55]

The solution of the optimization problem and the sensitivity analysis results indicates several important findings. For instance, the PLA and the ADV INC stand out as the most efficient technologies to create the WtE conversion, provided that there are sufficient funds to build and run these facilities. If there are economic restraints, the AD could be a more cost-effective way to create energy from waste. If CO_2 emissions are another important concern for utilizing WtE technologies, the PYR and the PLA would be favored even further.

Nevertheless, generalization of the results to different settings is impossible since the solutions can be very parameter-sensitive. The strategic decisions regarding the usage of different WtE methods in MSW management of a country should consider the possible changes in the cost and effectiveness of WtE technologies in the near future. Moreover, despite the additional analysis on reducing CO_2 emissions, one should note that the analysis of the current study is more from an economic point of view, and there can be other socioeconomic, environmental and technical concerns in forming strategic decisions to build WtE facilities. Considering the waste as another input for the circular economy, using WtE technologies enhances circular economy practices. Moreover, one of the main goals of WtE is to reduce GHGs and eliminate inputs from fossil raw materials, in other words, decarbonization.[40,56] Thus, combining WtE with the circular economy creates a double-positive result. In addition to this, building and operating more WtE facilities would contribute to social development, job creation, and income of the local societies. A more comprehensive analysis in this matter could be achieved by formulating a multicriteria decision model that encompasses all of these dimensions to decide on the weight of the WtE technologies to be used in a particular region. Our future research agenda includes this kind of an analysis procedure. Still, we believe that the insights obtained here could be helpful and illuminating to the policymakers in developing strategic plans of investment and planning for the best combinations of WtE technologies to use in the future.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Irem Firtina-Ertis https://orcid.org/0000-0002-7841-4209

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