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Research Article

A study on the renewable energy potential of incineration of municipal solid wastes produced in Izmir province

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ABSTRACT

The efficient use of existing energy sources along with the development and widespread use of alternative energy sources, especially renewable energy sources becoming important issues. At this point, the energy content of municipal solid wastes (MSW) can be considered a renewable energy source. MSWs contain a large fraction of renewable material and are continuously produced as a result of human activity. Therefore, international authorized institutions such as the U.S. Department of Energy (US DOE), and the U.S. Environmental Protection Agency (US EPA) assess MSWs as renewable and sustainable energy sources. Incineration is one of the options for energy recovery from MSW as a waste-to-energy (WTE) approach. The R1 energy efficiency is a criterion introduced by the European Union Waste Directive (Directive 2008/98/EC) to differentiate waste operation by incineration as either disposal or energy recovery. The paper focused on the evaluation of the MSW incineration potential of İzmir province in consideration of R1 energy efficiency criteria. According to the R1, the MSW energy recovery (both heat and electricity) potentials were investigated considering the amount, composition, and calorific value of MSW generated in İzmir province. The population growth, MSW generation, and calorific value alternation up to 2026 were estimated for İzmir. Based on MSW future projections of İzmir province, overall energy recovery potential was assessed. It is forecasted that the average net calorific value (NCV) of MSW generated in İzmir will exceed 6 MJ/kg. This NCV will be suitable for energy recovery from the İzmir MSW. Assuming R1=0.65, it is predicted that a minimum of 2231 GWh/year of heat energy or 932 GWh/year of electricity can be produced annually in the next years 2022.

1. Introduction

Nowadays, one of the reasons for the steady increment in energy demand and dependence on energy is the growth of the World population, industrialization, and technological progress [1]. It is emphasized by energy experts that the fossil fuels in the world may run out [2]. Hence, searching for alternative energy resources especially renewables have gained great attention recently. Municipal Solid Waste (MSW) is considered a renewable energy resource because MSWs contain a large fraction of renewable material and are continuously produced. MSW is a heterogeneous material usually obtained from a collection of wastes generated in urban fields, which naturally alters from region to region. MSW contains a large fraction of renewable materials (or biomass feedstock) like food waste, cardboard, paper, grass clippings, leaves, wood, leather products, and other non-renewable (or non-biomass feedstock) materials like plastics and other synthetic materials made from petroleum [3]. The rational disposal of MSWs, which naturally arises as a result of our vital activities, is a very important issue in terms of providing maximum economic contribution as well as human health [4].

The US Department of Energy (US DOE) reported that MSW consists of 82% biomass (food, paper, yard wastes, rubber, etc.) and 18% petrochemical wastes, which are combustible materials. Therefore, the US DOE classifies the MSW in the biomass fuel category of renewable energy sources [5]. According to the US Environmental Protection Agency (US EPA), electricity and heat generation with non-recyclable waste materials can be considered renewable energy generation. This process reduces carbon emissions by reducing methane generation from landfills and offsetting energy needs from fossil sources [6]. Energy Information Administration (EIA) has assorted all consumption at MSW combustion facilities as

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a renewable part of "Waste Energy" [7].

Many countries focus on the policy of using these resources effectively to reduce the consumption of natural resources and struggle with the emerging energy crisis [8]. In this scope, energy generation from MSW is gaining increasing interest in terms of reducing dependence on fossil sources. Energy conversion from MSW in waste-to-energy (WTE) power plants is one of the main ways of integrated waste management. Hence, energy conversion from MSW, as a waste management strategy, is increasing in terms of both the number of facilities and capacity across Europe and, is supported by legal directives [9]. Waste-to-energy is recognized as a promising alternative and a potential renewable energy source to tackle the problem of waste generation [10]. The waste management hierarchy suggested by Directive 2008/98/EC [10] of The European Parliament and The Council Energy is shown in Figure 1. After reducing, reusing, and recycling, material, and energy recovery has a priority in waste management.

Incineration is defined as the controlled burning of waste at high temperatures, and it reduces the volume of waste, generates energy from waste as heat and power, and eliminates pathogens [11,12]. The main purpose of an incineration facility is the conversion of stored energy from waste to useful energy forms. MSW incineration process is composed of three main steps: combustion of MSW in an incinerator, energy recovery from flue gas, and cleaning of air pollutants. Incineration of MSW does not completely dispose of the waste but does remarkably reduce the volume of waste to be landfilled. The reductions via incineration are approximately 90 percent by volume and 75 percent by weight [13]. Some air pollutants, such as COx, SOx, and NOx, are formed because of the incineration of MSW. In the past, MSW incinerators were considered major sources of such environmental pollutants. On the other hand, the WTE power plants implemented new US EPA regulations on Maximum Achievable Control Technology (MACT) during the 1990s, and then, they have become one of the cleanest sources of heat energy and electricity [14].

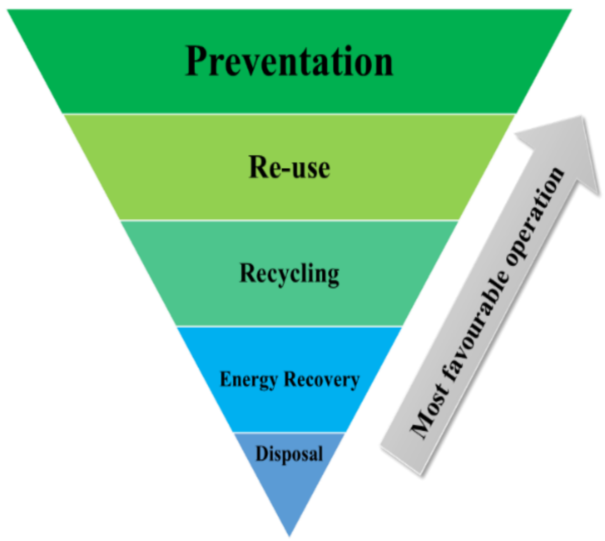

Figure 1. Waste management hierarchy [10]

One of the important issues is the energy conversion efficiency of the input waste during incineration. In this study, R1 efficiency was adopted for waste incineration energy conversion. The criterion of energy efficiency (R1 formula) that was introduced in the Waste Framework Directive in 2008 [10] is an incentive for WTE plants in Europe to improve their efficiency. According to Annex II of the Waste Framework Directive, incineration facilities dedicated to the processing of MSW can be classified as R1 recovery operations where their energy efficiency is equal to or above 0.65 for new plants [10]. In other words, the R1 threshold should be satisfied on the condition that a minimum of 0.65 for energy recovery via MSW incineration. Gohlke [15] investigated efficiency energy recovery from MSW and the resultant effect on greenhouse gas balance. The author reported some energy efficiency performance indicators and concluded that the R1 criterion will lead to the development and implementation of the optimized process and system. Grosso et al. [16] analyzed the R1 formula and exergy efficiency of 97 European plants as energy recovery criteria. According to their study, 43.7% of 97 European WTE plants have R1 efficiency higher than 0.65. In this respect, the energy potential via incineration was theoretically assessed for MSW generated in İzmir using the R1 criteria in this study. According to the R1 criteria, R1=0.65 is the threshold value for energy recovery in incineration facilities. Thus, in the scenario of establishing an incineration plant in İzmir, the energy recovery efficiency of the incinerator should be at least R1=0.65. Different from the other study in the literature, a 0.65 threshold value of R1 efficiency was adopted to determine the theoretical potential of energy content which can be recovered from İzmir province MSW by the way of incineration. The total produced energy from the MSW in İzmir was calculated assuming the 0.65 value of the R1 efficiency is the minimum value for the energy recovery and it can be increased, but the calculations have been made using this threshold value as the worst scenario for energy recovery from MSW.

İzmir is the third big city in Turkey with a population of nearly four million. It is located in the western region of Turkey and is on the Aegean Sea coast. İzmir is the industrial and tourism center of the Aegean Region and a prospering province in both economy and population. In the present paper, an investigation of the energy potential of MSW in İzmir using incineration technology was carried out. The main objective of this study is to quantitate the contribution of MSW in İzmir to the energy production of the city via the MSW incineration option. This paper provides the theoretical potential of energy content that can be recovered from MSW by the way of incineration and evaluation of the energy potential of MSW in the city according to R1 energy efficiency [10]. Different from the other study in the literature, the current study investigates the incineration potential of MSW generated in İzmir province. As stated earlier, a 0.65 threshold value of R1 efficiency was adopted in this study to assess the theoretical potential of the energy content of MSW generated in the İzmir province. The population growth, MSW generation, and energy amount projections from 2022 to 2026 were also presented in this study.

2. Methodology

The energy content of MSW is the major energy input of the MSW incinerator. The energy content of MSW as an energy source is strictly linked to two parameters: net calorific value (NCV) and quantity of MSW. The energy content of MSW ($\dot{E}_w$) can be written as in Eqn. 1.

$$\dot{E}_w = \dot{m}_{waste} NCV_{waste} \quad (1)$$

where $\dot{m}_{waste}$ is the MSW feed rate to the incineration facility and NCV_{waste} is the net calorific value of the MSW. This is because the calculation and estimation of the generation rate and net calorific value of MSW are important for the feasibility of an incineration plant. In this study, the calculation and estimation of the generation rate and net calorific value of MSW produced in İzmir have been conducted.

2.1. MSW generation in İzmir

The waste continuously is generated as a result of human activity. Therefore, the population future projection is one of the important parameters for the estimation of MSW generation. İzmir's yearly population growth and MSW generation data were obtained from official reports prepared by the Turkish Statistical Institution (TurkStat) in the current study. According to TurkStat statistics, the population of İzmir is gradually increasing and it is expected to be nearly 4.7 million in 2026 [17,18]. The population growth (from 2008 to 2021) and future projections (from 2022 to 2026) of İzmir city given in the TurkStat report can be shown in Figure 2 [19].

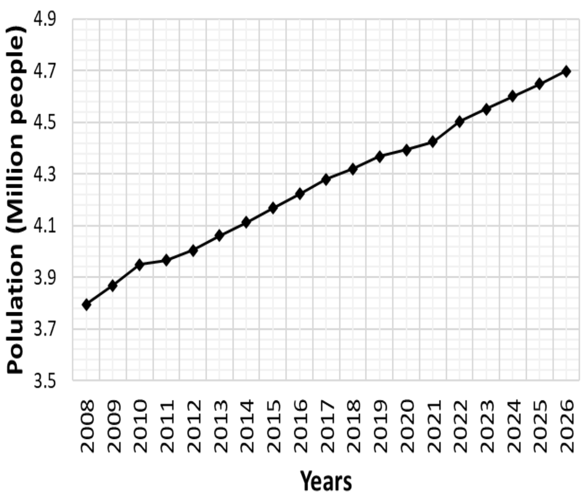

Figure 2. Population growth of İzmir city [17-19]

According to the waste generation data, which covers between 2001 and 2020 years, published by TurkStat, an average of 1.241 kg of MSW per day has been produced per person in İzmir province [16]. The data available indicate [20] that the average MSW generation in İzmir province is around 440 kg/capita/year. The annual MSW generation from 2008 to 2020 (orange bars) and future estimation (blue bars) of MSW generation from 2020 to 2026 in İzmir province are given in Figure 3. While the annual MSW generation between 2008 and 2020 given in Figure 3 is reported TurkStat data [20], the annual MSW generation between 2022 and 2026 is determined according to the past 2008-2020 MSW data using the least-squares method. It follows from the report prepared by TurkStat that total MSW generation in İzmir increased by 73.3% from 2008 to 2020. Also, it is expected that the MSW production amount is approximately 2.74 million tons per year in 2026. The economic development and growth of the urban population in İzmir province have increased the MSW amount.

2.2. Calculation of energy content of MSW

The energy content of the MSW can be determined experimentally by combusting the fuel in a high-pressure oxygen ambiance in a bomb calorimeter [21-23]. On the other hand, the complexity of biomass, particularly in case of MSWs, makes it highly difficult to experimentally estimate the calorific value (in other words energy content) [24]. The experimental approaches can be tedious, costly, and time-consuming [21]. Using theoretical approaches not only saves time but also saves high expenses [25]. There are different theoretical approaches in the literature to estimate and calculate the energy value of the MSW because of the non-homogeneous structure of MSW.

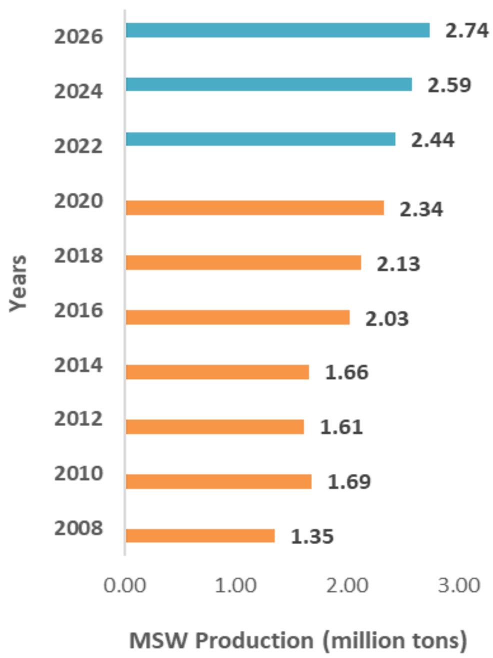

Figure 3. The annual MSW generation and future estimation in İzmir province [20]

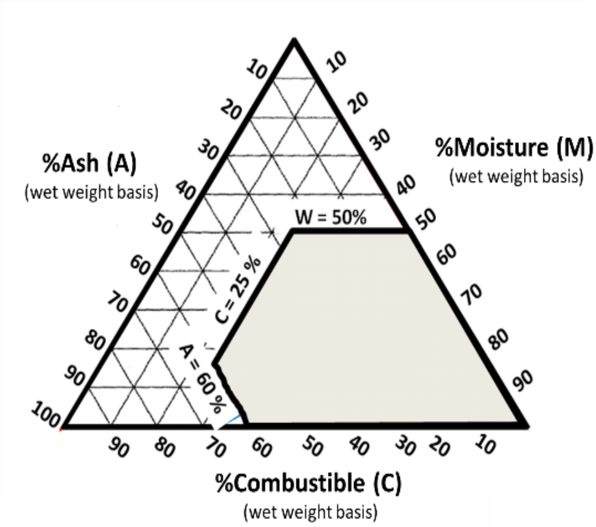

Figure 4. Tanner Diagram adapted from [28, 29]

One of the common theoretical approaches is ultimate analysis. This method is based on the elemental analysis for each component of the MSW that gives rise to the percentages of Carbon, Hydrogen, Oxygen, Nitrogen, Sulfur, and Chlorine elements. Then, the energy content of the MSW is determined depending on these chemical characteristics [24,26]. One of the more accurate ways to evaluate the fuel quality of waste is to divide it into characteristic components (organics, inert materials, plastics, cardboards, etc.). Thanks to this division, combustible matter (%C), water content (%W), and ash content (%A) of the waste are determined [12]. This approach is named proximate analysis. When the waste composition is defined accordingly proximate analysis, the Tanner diagram (Figure 4), which is the graphical plot of combustibility of MSW and based on actual field data from MSW incineration plant, can help to determine combustion characteristics of the MSW [27,28]. If MSW contains ash lower than 60%, moisture lower than 50%, and combustible higher than 25%, it can be said that MSW is suitable for incineration.

Together with proximate analysis, the approach developed for the feasibility studies of World Bank-supported projects was used to estimate the NCV of the MSW in this study. The NCV is calculated using the following expression [30].

$$NCV_{waste} = NCV_{awf}.C - 2445.W \quad (2)$$

where NCV_{waste} is the net calorific value (or lower calorific value) of the waste, NCV_{awf} is ash and water independent heating value of waste, C and W are combustible and moisture fractions of waste, respectively. Table 1 exhibits the fraction basis and calorific values of MSW that are calculated based on Eqn (2).

To determine the composition of MSW in İzmir, waste characterization analyzes are carried out by İzmir Metropolitan Municipality in 17 districts of İzmir, including the summer and winter months [31]. This waste characterization analysis was conducted for the years between 2008 and 2013 as well as 2018, and it was reported for these years. Waste composition percentages for 2014-2017 and 2019-2026 are estimated using the least square method. In other words, future projections of the composition for 2014-2017 and years after 2018 were made with curve fitting using the past data (2008-2013 and 2018 [31]). Composition percentages and future projections of İzmir MSW are given in Table 2.

2.3. The R1 energy efficiency formula

The R1 is defined to differentiate waste operation by incineration as either disposal or energy recovery of MSW based on threshold values of 0.60 and 0.65. Recovery takes place if R1>0.65 for plants permitted during 2009 and later, and for older plants R1>0.60.

$$R1 = \frac{E_p - (E_f - E_i)}{0.97(E_w + E_f)} \quad (3)$$

Table 1. Fractions and calorific values of waste components reported by the World Bank [12]

Fraction	Fraction Basis			Calorific values	
	Moisture W %	*Ash* A %	*Combustible* C %	NCV_{awf} kJ/kg	*NCV* kJ/kg
Food and organic waste	66	13.3	20.7	17000	1905
Plastics	29	7.8	63.2	33000	20147
Paper & cardboard	47	5.6	47.4	16000	6435
Wood	35	5.2	59.8	17000	9310
Metals	6	94	0	0	-147
Glass	3	97	0	0	-73
Inerts	10	90	0	0	-245
Textiles	33	4	63	20000	11793
Leather and rubber	11	25.8	63.2	23000	14267
Fines	32	45.6	22.4	15000	2578

Table 2. Composition percent of the MSW generated in İzmir [31]

Composition percentages	2008	2009	2010	2011	2012	2013	2018	2020	2022	2024	2026
Food and organic waste	48.78	39.71	49.1	54.66	46.71	56.4	45.41	49.56	49.68	49.80	49.92
Plastics	8.31	7.23	8.36	9.49	14.91	11.92	10.05	12.43	12.76	13.08	13.40
Paper & cardboard	12.97	11.16	9.45	9.63	12.96	8.44	6.81	10.11	10.10	10.09	10.07
Wood	1.12	4.70	0.85	1.29	1.94	0.96	1.24	1.38	1.33	1.29	1.24
Metals	1.78	0.42	0.51	0.65	1.24	0.97	0.98	0.93	0.93	0.92	0.92
Glass	5.37	5.09	4.43	5.37	6.55	4.97	6.63	5.49	5.49	5.49	5.49
Inerts	1.71	11.21	0.73	2.12	1.25	0.83	1.42	2.78	2.79	2.79	2.80
Fines	11.18	5.8	5.02	2.79	0	3.46	5.17	4.77	4.77	4.77	4.77
Other combustible	8.16	13.23	8.42	12.53	12.87	9.83	17.62	11.81	11.82	11.82	11.82
Others	0.25	0.75	12.87	0.003	0	0	2.32	2.31	2.31	2.31	2.31
Hazardous waste	0.31	0.56	0.13	1.01	1.5	1.79	1.14	0.92	0.92	0.92	0.92
Waste electrical and electronic devices	0.07	0.14	0.13	0.41	0.07	0.43	0.32	0.22	0.22	0.22	0.22

Reported data in ref. [31] (years 2008–2018)
Estimated data with least square method using reported past data in ref. [31] (years 2020–2026)

where E_p is produced energy (electricity or heat), E_w is the energy content of waste. E_f and E_i are the auxiliary fossil fuel energy and imported energy, respectively.

If no fossil fuels are burned and no auxiliary energy is needed, the R1 energy equation can be simplified as below:

$$R1 = \frac{E_p}{0.97E_w} \tag{4}$$

The factor 0.97 in the dominator is meant to take care of heat losses due to radiation and bottom ash [32]. The term E_p is calculated as defined by [32]:

$$E_p = 1.1\left(Q_{district} + Q_{process}\right) + 2.6\, W_{electric} \tag{5}$$

The terms $Q_{district}$ and $Q_{process}$ stand for heat delivered to district heat and facility internal process heat networks [32]. In other words, $Q_{district}$ is the heat energy that can be produced for district heating purposes (for example, example, residential heating). Similarly, $Q_{process}$ is the amount of heat that can be needed in the internal processes of the facility (for example, the production of hot water for use in internal processes in the facility). The sum of $Q_{district}$ and $Q_{process}$ is total heat (Q_{total}) produced in the plant. Another term $W_{electric}$ represents the produced electricity.

When the incineration plant is designed to convert waste energy to electricity, produced electricity ($W_{electric}$) according to the R1 formula becomes

$$E_p = 2.6\, W_{electric} = 0.97\, R1\, E_w \tag{6}$$

$$W_{electric} = \frac{0.97\, R1\, E_w}{2.6} \tag{7}$$

Similarly, when the incineration plant is designed to convert waste energy to heat, produced total heat (Q_{total}) according to the R1 formula becomes

$$E_p = 1.1\, Q_{total} = 0.97\, R1\, E_w \tag{8}$$

$$Q_{total} = \frac{0.97\, R1\, E_w}{1.1} \tag{9}$$

3. Results and Discussion

İzmir is a prospering province both in economy and population. The population of İzmir is gradually increasing and it is expected to be nearly 4.7 million in 2026. This population growth gives rise to an increase in the amount of generated MSW. Incineration facilities have been notable in that both the generated MSW can be disposed of and the energy conversion of MSW can be performed.

In this study, the calculation method proposed from the World Bank report is applied for the NCV of the MSW components. The NCV values of the MSW components, which were calculated with Eqn. (2), are listed in Table 1. The NCV of the MSW produced in İzmir was calculated based on the fraction basis of the MSW for the years. The overall NCV of the MSW generated in İzmir was calculated with Eqn. (10):

$$NCV_o = \sum_i x_i \times NCV_i \tag{10}$$

where NCV_o is overall NCV of the MSW x_i is composition percentage of the composition i and NCV_i is the net calorific value of the composition i (Table 1). As stated earlier, the composition percentage, x_i was estimated for 2014-2017 and 2019-2026 (Table 2). Therefore, the NCV of the MSW for İzmir was calculated for 2008-2013 and 2018 and estimated for 2014-2017 and 2019-2026 using Eqn. (10) for the years. "Others", "Hazardous waste" and "Waste electrical and electronic devices" in Table 2 were not involved in the NCV calculation due to the fact that they are not suitable for incineration. "Other combustible" in Table 2 was considered textiles, leathers, and rubbers. Therefore, the NCV value of "Other combustible" (NCV_i) was assumed as 13030 kJ/kg which is the arithmetical average of the NCV values of textiles, leathers, and rubbers [12]. Calculated and estimated NCV of the MSW generated in İzmir are given in Figure 5. It can be easily seen from the figure that the NCV has increased over the years. This increment means that the energy content of the MSW enhances and the usability of the MSW as a fuel in the incineration facilities rises. The average NCV of the MSW in İzmir was calculated as 6634.9 kJ/kg using the Eqn. (2). According to the report published by World Bank, the average net calorific value of the waste should not be less than 6 MJ/kg throughout all seasons to be able to incinerate the waste [12]. It is expected that an incineration plant to be installed for the evaluation of MSW with this calorific value is suitable for energy recovery.

The total energy that can be produced from MSW in İzmir assuming R1=0.65 is represented accordingly by years and future projections in Figure 6. It is observed from Figure 6 that the total annual produced energy (E_p) exceeds 2452 GWh in the next years of 2022. This estimated energy potential of the MSW can be used to meet the energy demand of İzmir province in the form of heat and electricity. According to the TurkStat, 2452 GWh energy value is equal to nearly 0.89% of the gross generation of electricity in Turkey. In 2016, 8.6% of Turkey's electricity need was met from renewable energy sources. It is expected that this estimated energy potential of MSW can contribute to meeting energy demand from renewable energy sources. In other words, the incineration of MSW produced in İzmir can contribute to the increase of 8.6% renewable energy in Turkey with an energy value of 2452 GWh.

The electricity and heat energy potentials of the incineration plant for İzmir province were calculated using Eqn. (7) and Eqn. (9). The electricity potential means that total electricity can be produced if the incineration plant is designed to convert MSW energy to electricity. Similarly, the heat energy potential means that total thermal energy can be produced if the incineration plant is designed to convert MSW energy to heat energy. The calculated and estimated potentials are given in Figure 7. The total electricity consumption in İzmir was nearly 19241 GWh/year in 2016 and 20433 GWh/year in 2019 [33]. It follows from Figure 7 that electricity from MSW with 852 GWh/year could meet nearly 4.43% of the electricity demand of İzmir in 2016. This percentage is encouraging for the establishment of the incineration plant in İzmir province. Also, producible heat energy with R1 criteria is the level that can be used in district heating. The great majority of the heat energy demand of both homes and industry has been met by natural gas in İzmir. The incineration facilities can be a versatile and environmental alternative to natural gas combustion systems for İzmir province. It can be also seen from Figure 7 that heat energy potentials are higher than the electric potential. The main reason for this situation is that the heat conversion rate of energy of waste is higher than the electricity conversion rate in incinerators.

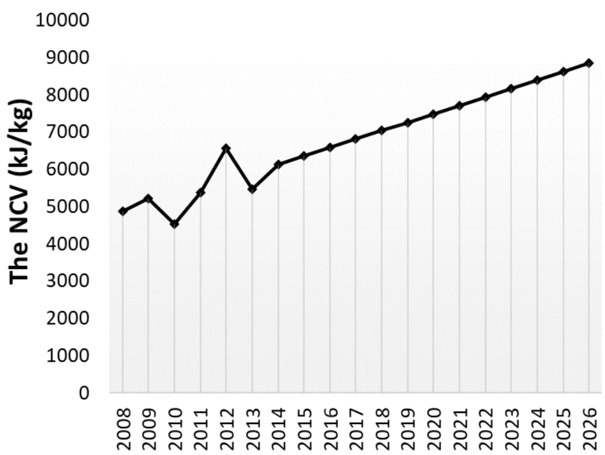

Figure 5. Calculated and estimated NCV of the MSW generated in İzmir [31]

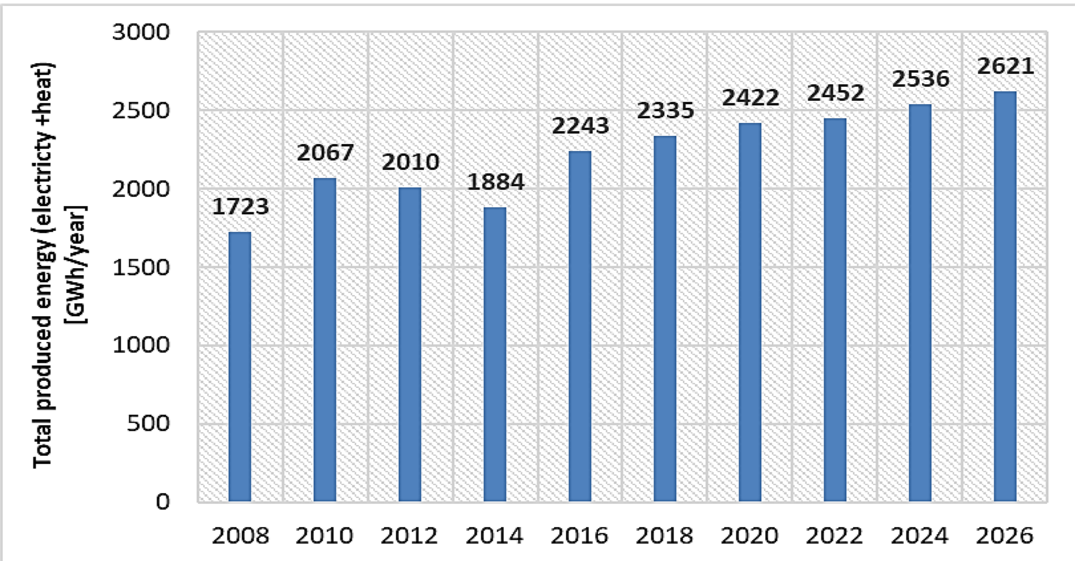

Figure 6. The energy potential of the MSW generated in İzmir province

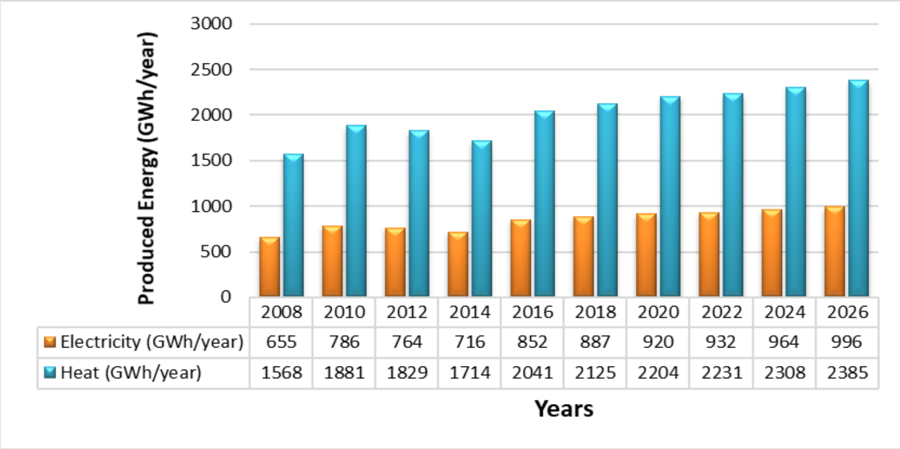

Figure 7. Estimated and calculated heat energy and electricity potentials of the MSW generated in İzmir province

4. Conclusion

The present study has been conducted to assess the energy potential of MSW generated in İzmir in terms of R1 energy efficiency. The MSW generation rate, based on population, the MSW energy content depending on waste fractions, and then heat energy and electricity potentials have been calculated and estimated with the future projections. The results show that;

- In the İzmir province, the population and MSW generation per capita has been increasing. Because of these increments, the overall MSW generation is estimated to be over 2.4 million tons per year after 2022. This amount of MSW can be used for energy recovery with aim of both overcoming waste problems and meeting energy needs.
- It is expected that the NCVs based on the MSW composition show rising over the years. It is forecasted that the average NCV will exceed 6 MJ/kg. This calorific value is suitable for energy recovery from waste. Therefore, the MSW generated in İzmir can be used as a renewable energy source for energy recovery.
- With the assuming R1=0.65 (threshold value of R1 energy efficiency for energy recovery in an incineration plant), it is predicted that a minimum of 2231 GWh/year of heat energy or 932 GWh/year of electricity can be produced annually the next years of 2022. This energy potential can be used to meet energy demand in İzmir with a properly designed incineration plant. It is evident that the evaluation of MSW in incineration plants can contribute to the renewable energy production of İzmir city.

Declaration

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author also declared that this article is original, and was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

A.Basaran developed the methodology, performed the analysis, and improved the study. A. Basaran wrote and proofread the manuscript.

Nomenclature

A : Ash content
C : Combustible matter content
E_f : Auxiliary fossil fuel energy
E_i : Imported energy
EIA : Energy Information Administration
E_p : Produced energy (electricity or heat)
E_w : Energy content of waste
$\dot{E}_w$: Energy content of MSW
MSW : Municipal Solid Waste
$\dot{m}_{waste}$: MSW feed rate to incineration facility
NCV : Net calorific value
NCV_{awf} : Ash and water independent net heating value
NCV_i : Net calorific value of the composition i
NCV_o : Overall NCV of the MSW
NCV_{waste}: Net calorific value of the MSW
$Q_{district}$: Heat delivered to district heat
$Q_{process}$: Facility internal process heat networks
Q_{total} : Produced total heat ($= Q_{district} + Q_{process}$)
$TurkStat$: Turkish Statistical Institution
US : The United States
$US\ DOE$: The US Department of Energy
$US\ EPA$: The US Environmental Protection Agency
WTE : Waste-to-Energy
W : Water (moisture) content
$W_{electric}$: Produced electricity
x_i : Composition percentage of the composition i

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