Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
A comparison between a natural gas power plant and a municipal solid waste incineration power plant based on an emergy analysis

Shima Yazdani a, Erfan Salimipour a,*, Mojtaba Saei Moghaddam b

a Department of Mechanical Engineering, Quchan University of Technology, Quchan, Iran
b Department of Chemical Engineering, Quchan University of Technology, Quchan, Iran

Article info
Article history:
Received 31 October 2019
Received in revised form 3 May 2020
Accepted 29 June 2020
Available online 17 July 2020
Handling Editor: Cecilia Maria Villas Boas de Almeida

Keywords:
Emergy analysis (EmA)
Natural gas power plant (NGPP)
Municipal solid waste (MSW)
Environmental impacts

Abstract
This paper performs an emergy analysis (EmA) to compare two real power plants include a conventional natural gas steam power plant (NGPP) with one that burns municipal solid waste (MSWPP). For this purpose, the EmA is used to investigate the sustainability, renewability, environmental impacts, and economic issues. The capacity of the NGPP and MSWPP are 247.5 and 3 MW, respectively. Results from this study show that the percent of renewability (PR) and emergy sustainability index (ESI) of the MSWPP are much more than those of the NGPP. The PR and ESI of the MSWPP are 46.81 and 1.65, while for the NGPP are 5.01 and 0.05, respectively. It is proved that the MSWPP is more efficient and has the better environmental impacts compared to the NGPP. Moreover, a hypothetical MSWPP with the same electricity output of the NGPP is studied using the EmA. A more efficient system with the higher PR and ESI is observed compared to the other case studies. Beside of these advantages, use of the MSW has other benefits such as reducing the greenhouse gases released in the atmosphere, saving fossil fuels, low land area required compared to the landfill, speed and ease of disposal, and production of clean and useful ash.

© 2020 Elsevier Ltd. All rights reserved.

1. Introduction

Almost 80% of the world’s electricity is generated by fossil fuels (coal, oil, and natural gas) that major portion of this electricity is produced in thermal power plants (Ahmadi and Toghraie, 2016). Thermal power plants (TPP) have been used in different kinds of industrial processes for about 100 years. Heat extracted from fuel is the main energy resource for these systems. In a steam power plant, by heating the water in boiler, it converts to a high-pressure steam and prepares to pass through the turbine blades. As a consequence, the generator will be turned and electricity is generated. Using the fossil fuels causes the negative environmental impacts such as air pollution, direct human health impact, and ecosystems damage. For sustainable development, long-term approaches and actions are needed to solve today’s global environmental problems (Esen et al., 2006). In this regard, the renewable energy resources such as wind, biomass, solar energy, hydropower, geothermal, and ocean energy have been developed (Rezaei et al., 2018; Esen and Yuksel, 2013).

One of the relatively new ways to generate electricity is to generate electricity from waste. Since waste management is one of the main problems in the world (Tarr, 1996), generated energy from the waste is an appropriate way. Composting, landfilling and incineration of the MSW are traditional ways to the disposal of urban waste. The power generation is the aim of some of the above-mentioned processes, and in others, the waste disposal is a priority. Nowadays, a proper management approach based on the sustainable development principles is that waste must be restored or reused as a potential source (T. U. N. E. P. (UNEP), 2004; Dijkema et al., 2000; Seadon, 2010; Brunner and Rechberger, 2015; Leckner, 2015; Rogoff, 2013; Korhonen et al., 2003). To choose a proper waste management system, these ways were compared by different approaches such as life cycle assessment (LCA) (Zhou et al., 2018; Liamsanguan and Gheewala, 2008a) and economic analysis (Santos et al., 2019). Zhou et al. (Zhou et al., 2018) by use of the LCA method found out that the incineration of the MSW is an appropriate solution because of its benefits (it has better environmental performance) compared to the other waste disposal methods. An appropriate solution can be incineration the MSW because of its benefits respect to other waste disposal methods. The heat released from the incineration the municipal
solid wastes (MSW) can be used as the input energy to TPPs. Many researchers investigated this method and presented some advantages of the MSW incineration such as decreasing the land needed compared to the landfill, independence of the weather conditions, production of the clean ash, disposal of dangerous waste, reducing the pollution of the air, and reducing the risk of the surface water pollution (Fei et al., 2018; Vlaskin, 2018; Cheng and Hu, 2010). By electricity generation from municipal waste, in addition to decreasing the fossil fuel consumption, the greenhouse gas emissions (GHG) vanish that are released as a result of waste dumping in the environment. However, for waste management, MSW incineration also generates dangerous gases and it cannot be claimed that waste incineration helps to reduce the GHG compared to landfills. But by considering this fact that a high portion of the electricity is generated by utilizing fossil fuels, it can be concluded that the GHG is made anyway (with using fossil fuels or MSW). So, one can only express that incineration of the waste could help to prevent the GHG due to the landfills.

One of the challenges of renewable energy resources is related to economic issues (Esen et al., 2007). Hence, using a method that could consider economic matters as same as the environmental subject is interesting. This method was introduced by Odum (1996) for the first time, is a system-emergy method used on a system-emergy basis (2016) called energy ecology (Wang et al., 2018). Emergy is the available solar energy that directly or indirectly utilized to make a product or give a service (Odum, 1996; Brown and Ulgiati, 1997). It means that this method has the ability to unify different kinds of energy, material, goods, and services into the common unit (solar energy joule). Recently, the emergy analysis (EmA) has been used in a wide range of research fields. The EmA research studies were concluded as the evaluation of the agriculture productions (Wifart et al., 2013; Bergquist et al., 2011), industry (Li et al., 2016), building and construction (Cristiano and Gonella, 2019; Cheng and Cheng, 2017), energy storage systems (Yazdani et al., 2019), urban sustainability (Lee and Brahiam, 2019; Hossaini and Hewage, 2013), and modern renewable systems (Yang and Chen, 2014; Siracusa et al., 2007). Some of these studies were performed to assess a proper way for the MSW management. Wang et al. (Wang et al., 2018) evaluated the performance of an integrated MSW incineration system using the EmA. They compared three alternative scenarios for an existing incineration power plant in order to make a decision for the waste management. Liu et al. (2013) performed an emergy analysis to compare the current landfill systems in Liaoning Province, China and three garbage treatment systems, including sanitary landfill system, fluidized bed incineration system, and grate type incineration system. They concluded that the EmA is a useful tool, which can be used to compare the comprehensive performances of different processes of urban solid waste treatment for decision-making and whole process optimization. Marchetti et al. (2007) used the EmA for evaluating the three traditional forms of waste treatment to assess a strategy for waste management.

According to the importance of the sustainability evaluation of various power plants, some researchers (utilizing the EmA) have studied on this subject. Brown and Ulgiati (Brown and Ulgiati, 2002) made a comparison between six power generation systems using the EmA. They investigated both plants using renewable energy sources (hydroelectric, geothermal, and wind plants) and nonrenewable energy sources (natural gas, oil, and coal thermal plants). They found that the wind and hydroelectric plants had the highest-over-all aggregated (economic and ecological) sustainability, followed by geothermal electricity. Furthermore, Li et al. (2016) conducted the emergy analysis to evaluate the environmental efficiencies of seven utility boiler energy conversion systems. Their results indicated that the natural gas boiler had the highest sustainability compared to the other fossil fuel boilers. They also concluded that the solar boiler could be widely used if its capital cost and the O&M cost decreased. Their results demonstrated that the biomass boiler has the best emergy sustainability index.

In the previous research studies, waste incineration for energy production as a method of waste management has been investigated. Fossil fuel power plants have also been studied in the previous studies. But in none of them, these two types of power plants have been compared by using emergy analysis. In this paper, an emergy analysis is carried out to compare two power generation systems: a power plant based on natural gas fossil fuel (NGPP) and an MSW power plant (MSWPP). For this purpose, the Besat natural gas power plant (BNGPP) and the Aradkouh MSW power plant (AMSWPP) located in Tehran, Iran are studied. The installed capacity of the BNGPP and AMSWPP are 247.5 MW, and 3 MW, respectively. At stage one, the EmA is conducted for evaluating their performance and environmental sustainability and a comparison is performed for the emergy-based indices, including transformation ratio known as solar transformity (Tr), percent renewable (PR), emergy yields ratio (EYR), environmental loading ratio (ELR), and emergy sustainability index (ESI). In order to investigate more accurately, in the next step, a hypothetical MSWPP with the same electricity output of the BNGPP is analyzed. The same electricity outputs can help to a better comparison between two systems.

2. Introducing the case studies

The BNGPP is located in Tehran, Iran. This infrastructure is the type of fossil fuel power plant. It has three units with the total capacity of 247.5 MW. This power plant is a part of the grid power line of Iran, which for the first time in 1966 was constructed with the capacity of 230 KW. Fig. 1 shows a view of this power plant. The BNGPP works based on the Rankine power cycle. In the early years, the main fuel of this power plant was heavy diesel and gas oil but it now has dual-burning burners and there is the possibility of using natural gas. The raw water of the plant is provided by five wells. Moreover, the plant contains the extraction turbines.

Another investigated case is the AMSWPP that was constructed in 2015 in Tehran, Iran. The waste from all over Tehran is collected in the Kahrizak district (south of Tehran). Due to the lack of the separation of the waste by the people at source, first the waste is to be separated by the workers, and then the part of the waste containing food is transported to a place with an area of 40 ha; after a month, it completely loses its moisture and is turned into the fertilizer. A portion of the waste, including nylon and non-recyclable plastics are transferred to the waste incinerator and will be used there. The Aradkouh MSWPP was constructed by Iranian experts with cooperation of a US-licensed company by the aims of reducing the environmental impacts, social costs, and by considering the global approach to energy production from waste. The investment cost of this power plant is 13 million dollars and the construction cost per year with a lifetime of 20 years, is 0.65 million dollars. Currently, in the AMSWPP near 200 tons per day of the MSW is processed in waste-to-energy units for producing 3 MW electricity. Fig. 2 shows a view of the AMSWPP. This power plant consists of a waste pit and its input is the result of the processing and separating of the household wastes of Tehran, office buildings, equipment buildings, and refinery. The MSW enters from the pit to the circulating fluidized bed to burn at a temperature of 800–1200 °C. In the middle zone of the burner, by making the vacuum conditions, the MSW breaks down to the several gases. Then in order to mix the gases with the air to burn completely, the MSW enters the second burner. In fact, the temperature of 800–1200 °C in the first furnace removes dangerous gases such as dioxin, and the other hazardous gases eliminate by the second furnace with the temperature of 950–1005 °C. This power plant uses a non-condensing turbine,
known as back-pressure turbine.

3. Emergy analysis (EmA) procedure

EmA was proposed by Odum in 1980s (Odum, 1996), as a method to evaluate the energy, economic and environmental impacts of a system (Wanget al., 2018). EmA is a useful tool to analyze systems energy efficiency through considers all the different process inputs and outputs, such as energy, fuel, labor, money, and natural resources, in solar energy equivalents (Li et al., 2016). The amount of solar energy that directly or indirectly, has been previously required to produce a product or service is defined as emergy, hence its unit is the solar emergy joule (seJ) (Odum, 1996). The emergy amount for each input source of the system is obtained as follows:

\[ Em_i (\text{seJ}) = Tr_i (\text{seJ/unit}) \times Ex_i (\text{unit}) \]  

(1)

where \( Em_i \), \( Tr_i \) and \( Ex_i \) are the emergy, transformity and exergy of the \( i \)th source, respectively. To evaluate the emergy of the system components, a quantity so-called solar transformity \( (Tr) \) is needed. The solar transformity (with unit of \( \text{seJ/unit} \)) is defined as the emergy amount required for each unit of input or product; or in the other words it is the ratio of emergy (work put into a product (input)) to exergy (energy that is available to be used (output)). The transformity for each source can be find from the previous research studies. After the summation of all the input energy values, the transformity of the system output (electricity in this study) can be obtained as follows:

\[ Tr_{out} = \sum \frac{Em_i}{Ex_{out}} \]  

(2)

where \( Ex_{out} \) is the output or in the other words is the available energy of a product or service (amount of electric power in this study).

The emergy indicators can help to compare the production of each system. These indicators are defined as follows:

1) Energy Yields Ratio \( (EYR) \):

\[ EYR = \frac{Y}{NP + RP} \]  

(3)

where \( RP \) denotes the purchased renewable emergy.

2) Environmental Loading Ratio \( (ELR) \):

\[ ELR = \frac{NR + NP}{R + RP} \]  

(4)

where \( NR \) is the free non-renewable emergy.

3.1. Emergy sustainability index \( (ESI) \)

\[ ESI = \frac{EYR}{ELR} \]  

(5)

Fig. 1. Schematic of the best natural gas power plant (BNGPP).

Fig. 2. Schematic of the Aradkouh MSW power plant (AMSWPP).
4) Percent of Renewability (PR):

\[ PR = \frac{R + RP}{Y} \]  

(6)

The details of computations of these emergy indices can also be shown in Ref. (Yazdani et al., 2019).

The emergy evaluation procedure utilized in this study begins with overview diagramming for recognizing sources and pathways in a system, organizing the EmA tables, determining the emergy indices and ratios, and making comparisons between the power plants. For the emergy analysis, it is necessary to classify all the system inputs into the renewable (R) and non-renewable (N) sources. Each renewable or non-renewable source can also be free or purchased. The whole processes carried out in the current study are shown as a flowchart in Fig. 3. The emergy analysis utilized in the present study includes seven parts as follows:

1) Preparing the emergy diagrams,
2) Exploring all inputs quantity of the BNGPP and AMSWPP per one year, such as the amount of natural gas and MSW,
3) Finding the transformities of inputs from the emergy-based references,
4) Performing the emergy computations,
5) Presenting the EmA tables,
6) Calculating the emergy indices and ratios,
7) Comparing the power plants.

3.2. Emergy system diagrams

At the beginning of the emergy analysis, the emergy diagrams are prepared. These diagrams contain the whole of the paths and processes to obtain the products. The emergy diagrams for the BNGPP and AMSWPP are shown in Figs. 4 and 5, respectively. Now it’s time to prepare the emergy tables. Thus, the whole processes (all inputs consist of the resources, materials, labor and services), life cycle and exergy information of the power plants are explored. Moreover, the transformity of each input needs to be found. The total global annual emergy inputs emanated from the solar radiation, tidal momentum, and geothermal on the biosphere, are called geobiosphere emergy baseline (GEB) (Wanget al., 2018). Currently, there are six emergy baselines, i.e. 9.44E+24 seJ/year (Odum, 1996), 9.26E+24 seJ/year (Campbell, 1998), 15.83E+24 seJ/year (Odum, 2000), 15.20E+24 seJ/year (Brown and Ulgiati, 2010), 1.16E+25 seJ/year (Campbell, 2016), and 12.0E+24 seJ/year (Brown and Ulgiati, 2016). With the latest baseline, the transformities of other studies that were achieved by using different GEB can be converted as a transformity with newest GEB as follows:

\[ T_{\text{new}} = T_{\text{old}} \times \frac{\text{new emergy baseline}}{\text{old emergy baseline}} \]  

(7)

In the present paper, the newest emergy baseline (12.0E+24 seJ/year) is chosen as the baseline. The list of the transformities used in this study are presented in Table 1.

Table 2 presents the emergy calculations for the BNGPP. The analyses are performed for one year. The inputs of the BNGPP include the materials, capital cost, O&M, and services and labor’s work. R, NP, and Y in the table denote the free renewable resource, purchased non-renewable resource, and yield emergy (output), respectively. By considering the electricity output during one year and calculating the emergy for all the input sources, the transformity of the electricity generation in the BNGPP is specified. It is observed that the transformity of the electricity output is 7.06E+04 seJ/J. Table 3 presents the emergy calculations for the AMSWPP. The transformity of the electricity output from this incineration MSW power plant is equal to 7.10E+4 seJ/J. Therefore, approximately the same amount of the emergy is consumed to produce a unit of electricity in the BNGPP and AMSWPP. However, these two power plants generate different electric power amount. In order to perform a more accurate comparison between the BNGPP power plant and an MSW incineration power plant, a hypothetical MSWPP (HMSWPP) with the electricity output as same as the BNGPP (7.81E+15 J electricity output) is studied. Table 4 presents the emergy calculations for this hypothetical system. The transformity

![Flowchart of the emergy analysis procedure.](image-url)
of the electricity output from the HMSWPP is equal to 5.11E+04 seJ/J. In fact, to generate a unit of the electricity in the BNGPP, approximately 1.4 times more emergy is used compared to that of the HMSWPP. A larger transformity indicates a greater need for product generation and less energy efficiency.

4. Results

To visually describe the consumed emergy inputs by the inputs from different energy sources, the signature diagrams can be useful. Fig. 6 depicts the consumed emergy inputs for producing the output electricity in BNGPP. The oxygen and water were two inputs of the BNGPP system. This diagram shows that the total emergy of the non-renewable resources is higher than that of the renewable ones. Figs. 7 and 8 show the emergy inputs of the AMSWPP and HMSWPP systems, respectively. The MSW, oxygen, and water are the renewable inputs of these systems. As can be seen, in two power plants the renewable resources have a significant portion of the total inputs.
5. Discussion

Comparison of the emergy indices and ratios between the case studies can assess the performance and sustainability of each system. As shown in Table 5, the emergy indices of the three power plants studied in this paper are compared with the various power generation systems. EYR is an indicator to measure the ability of a process to utilize locally renewable and nonrenewable resources by investing outside resources. The higher the value of the EYR, because of lower purchased inputs, the better the economic benefit. EYR of 2.84 related to the HMSWPP means that the emergy of the yield is 2.84 times greater than the invested emergy. The EYR of the BNGPP is approximately one and it is lower than that of other cases. However, the EYR of the HMSWPP is only 2.84, much smaller than the 5.06 of the solar tower power plant, 7.65 of the hydro power plant, 5.48 of the coal-based thermal power plant, 4.81 of the geothermal power plant, and 4.21 of the oil-based power plant. The ELR helps to perform a complete assessment and estimates the potential environmental impacts of system. The increased capital investment and use of non-renewable resources can lead to higher ELRs. As expected, the ELR of the fossil fuel based power plants (BNGPP (20.82), coal (10.4), and oil (14.2)) have the higher ELR due to their dominant non-renewable fuel sources, which cause higher environmental impacts. It can be inferred that the HMSWPP has the less environmental stress. Wang et al. (Wanget al., 2018) investigated

| Table 2 | Energy analysis of the BNGPP. |
| Item | Item | Raw amount | Unit | Solar transformity (seJ/unit) | Solar emergy (seJ/year) |
| --- | --- | --- | --- | --- | --- |
| Inputs | R (item 1) | | | | |
| 1 | Oxygen (in air) | 3.85E+11 | g | 6.56E+07 | 2.53E+19 |
| NR (item 2) | | | | | |
| 2 | Water | 2.82E+12 | g | 8.44E+05 | 2.38E+18 |
| NP (sum of item 3–7) | | | | | |
| 3 | Natural gas | 8.21E+15 | J | 6.10E+04 | 5.01E+20 |
| 4 | Investment cost | 3.01E+06 | $ | 1.62E+12 | 4.88E+18 |
| 5 | Human labor | 9.50E+06 | $ | 1.62E+12 | 4.88E+18 |
| 6 | O & M | 1.51E+07 | $ | 1.62E+12 | 4.88E+18 |
| 7 | Land occupation | 2.00E+05 | m² | 1.02E+11 | 2.04E+16 |
| Output | Y | Electricity | 7.81E+15 | J | 7.06E+04 | 5.51E+20 |

| Table 3 | Energy analysis of the AMSWPP. |
| Item | Item | Raw amount | Unit | Solar transformity (seJ/unit) | Solar emergy (seJ/year) |
| --- | --- | --- | --- | --- | --- |
| Inputs | R (sum item 1 + 2) | | | | |
| 1 | MSW | 7.30E+10 | g | 3.89E+07 | 2.84E+18 |
| 2 | Oxygen | 4.65E+09 | g | 6.56E+07 | 3.05E+17 |
| NR (item 3) | | | | | |
| 3 | Water | 2.25E+10 | g | 8.44E+05 | 3.55E+16 |
| NP (sum of item 4–7) | | | | | |
| 4 | Fuels | 2.80E+12 | J | 8.39E+04 | 2.35E+17 |
| 5 | Investment cost | 6.50E+05 | $ | 1.62E+12 | 1.05E+18 |
| 6 | Human labor | 1.07E+06 | $ | 1.62E+12 | 1.05E+18 |
| 7 | O & M | 3.25E+05 | $ | 1.62E+12 | 1.05E+18 |
| 8 | Land occupation | 3.00E+04 | m² | 1.02E+11 | 3.06E+15 |
| Output | Y | Electricity | 9.46E+13 | J | 7.10E+04 | 6.71E+18 |

| Table 4 | Energy analysis of a hypothetical MSWPP. |
| Item | Item | Raw amount | Unit | Solar transformity (seJ/unit) | Solar emergy (seJ/year) |
| --- | --- | --- | --- | --- | --- |
| Inputs | R (sum 1 + 2) | | | | |
| 1 | MSW | 5.99E+12 | g | 3.89E+07 | 2.33E+20 |
| 2 | Oxygen | 3.85E+11 | g | 6.56E+07 | 2.33E+19 |
| NR (item 3) | | | | | |
| 3 | Water | 2.82E+12 | g | 8.44E+05 | 2.38E+18 |
| NP (sum of item 4–7) | | | | | |
| 4 | Fuels | 2.30E+14 | J | 8.39E+04 | 1.38E+20 |
| 5 | Investment cost | 3.25E+07 | $ | 1.62E+12 | 5.27E+17 |
| 6 | Human labor | 1.43E+07 | $ | 1.62E+12 | 5.27E+17 |
| 7 | O & M | 2.67E+07 | $ | 1.62E+12 | 5.27E+17 |
| 8 | Land occupation | 3.00E+05 | m² | 1.02E+11 | 3.06E+16 |
| Y | Electricity | 7.81E+15 | J | 5.11E+04 | 3.99E+20 |
three alternative incineration power plants (MSW incineration A: the incineration subsystem + the bottom ash landfill subsystem; MSW incineration B: the incineration subsystem + the concrete paving brick production subsystem using bottom ash as raw material; MSW incineration C: the incineration subsystem + the non-burnt wall brick production subsystem using bottom ash as raw material). They concluded that different disposal ways of bottom ash have various impacts on environmental loading due to their different input structure. By measuring the ESI, the sustainable performance for each system can also be obtained. The ESI accounts for economic and ecological compatibilities. As can be seen from the emergy indices in Table 5, the ESI of the fossil fuel based power plants are less than one; therefore, the production of these systems are not sustainable. The ESI of the AMSWPP is 1.65. It means that this power plant is moving toward a more sustainable system. For ESI >5, the system has greatly achieved its sustainability. The ESI of the HMSWPP is 5.32; thus, this power plant shows the best ecological performance and environmental sustainability compared to the BNGPP and AMSWPP. However the geothermal, hydro, and solar tower power plants have the highest sustainability.

The metropolis of Tehran, with an area of over 730 square kilometers and a population of around 8.4 million, is located on the southern slopes of central Alborz. In Tehran, the landfilling is the main municipal waste management system. About 9000 tons of municipal waste from Tehran is generated every day and there is no management after waste disposal in landfills, which are covered and abandoned (Khayamabshi, 2016). As the population of Tehran has increased sharply in recent years, the people are now settling in the Kahrizak area (near Aradkouh, the landfill site) that in the previous was exclusively for landfill. People are tormented by the
smell of garbage. Disposal of waste in an area close to where people live is both ugly and endangering the health of people. Especially, at the present situation that the coronavirus is propagating in Tehran, the hospital’s wastes are released without any arrangements in Arakdouh which may contain the coronavirus.

Landfilling is deemed as the main MSW disposal way, however, it is not considered as a sustainable procedure, due to land occupation, leachate leakage, and greenhouse effect from the methane gas emission (Wanget al., 2018).

Soil is the most important physical, chemical, and biological filter for water, waste recycling, etc., but its capacity is limited, and many toxic substances and contaminants added to the soil can pose a serious threat to the environment. The most serious cause of water contamination in landfill regions is leachate, which hazards human’s and animal’s health by entering groundwater.

In big cities a lot of wastes produce and require a large area to bury them; hence, waste landfilling does not seem to be a suitable method. Urban waste management is one of the ways to reduce the GHG. GHG have been proposed as one of the means for assessing the sustainability of energy sources, where those sources that release less gases are more sustainable than other sources that release more gases. Greenhouse gas monitoring can help to remove environmental concerns about global warming. The global warming potential (GWP) for a system can be defined as a mixture of the greenhouse gases including the carbon dioxide (CO₂), methane (CH₄), and Nitrous oxide (N₂O). Results of some research studies demonstrated that waste recycling will contribute to the smallest amount of GHG emissions, while incineration is second lowest (Chen and Lin, 2008; Liamsanguan and Gheewala, 2008b; Song et al., 2013). Use of the waste to energy (WtE) approach includes several advantages such as minimizing the waste volume, a source of renewable energy, and GHG emissions avoidance from fossil fuel sources (Islam, 2018). Two methods for WtE approach is waste incineration and LFG recovery system (Tan et al., 2014), however, the most economical solutions reported for the future energy system are mixed waste incineration (Münster and Meibom, 2011). The results from Islam (2018) showed that, WtE leads to CO₂ reduction in a region because providing heat and electricity from MSW reduces the amount of fossil fuels for heat and electricity generation. He concluded that MSW incineration can be considered as the optimal approach because of highest energy potential, profitability and climate benefit in terms of GHG emission reduction. Incineration of MSW leads to reduction of MSW mass (about 80%) and volume (90% or so). This may mitigate land resource constrains in densely populated regions (Wanget al., 2018). The experience of developed countries demonstrated that MSW incineration is a beneficial method for centralized MSW disposal (Lombardi et al., 2015; Marchi et al., 2017; Rajaeifar et al., 2017). However, incineration of MSW also includes some secondary environmental problems, such as ash remnant, and air pollution, which must be counted. WtE leads to CO₂ reduction in a region because providing heat and electricity from MSW reduces the amount of fossil fuels for heat and electricity generation (Tabata, 2013).

The results of the present paper, especially the energy indicators, demonstrate that an MSWPP is more sustainable and has less environmental impacts than a thermal power plant based on fossil fuels. In this method, in addition to energy production, the waste to energy is reduced and less area is required for landfill, as well as less smell in landfill areas and less groundwater pollution. In the MSWPP investigated in this study, only 200 tons per day MSW is converted to energy while the capacity of this process can be more than now. It is worthy to invest into MSW power plants in large cities that so much MSW generate every day.

![Fig. 8. Emergy signature diagram of the HMSWPP for a one-year period.](image-url)

### Table 5
Comparison of the emergy indices between this study and the related studies.

| Item                  | References | EYR | ELR  | ESI   |
|-----------------------|------------|-----|------|------|
| BNGPP                 | This study | 1.05| 20.82| 0.05 |
| AMSWPP                | This study | 1.88| 1.14 | 1.66 |
| HMSWPP                | This study | 2.84| 0.54 | 5.2  |
| MSW incineration A    | Wanget al. (2018)| 1.33| 11.06| 0.012|
| MSW incineration B    | Wanget al. (2018)| 1.34| 24.32| 0.055|
| MSW incineration C    | Wanget al. (2018)| 1.61| 14.07| 0.011|
| LEPS                  | Pan et al. (2018)| 1.18| 1.2  | 0.98 |
| Wind farm             | Yang and Chen (2016)| 1.77| 1.84 | 0.2  |
| Solar tower power plant| Zhang et al. (2012)| 5.06| 0.39 | 13.1 |
| Geothermal            | Brown and Ulgiati (2002)| 4.81| 0.44 | 11.0 |
| Hydro                 | Brown and Ulgiati (2002)| 7.65| 0.45 | 16.9 |
| Coal                  | Brown and Ulgiati (2002)| 5.48| 10.4 | 0.53 |
| Oil                   | Brown and Ulgiati (2002)| 4.21| 14.2 | 0.3  |
| Biogas                | Wang et al. (2014)| 1.63| 1.11 | 1.47 |
6. Conclusions

In this paper, an emergy analysis was performed to compare a conventional natural gas powered thermal plant with one that burns municipal waste. The analysis included an assessment of two real plants, as well as a comparison between the fossil fuel power plant and a hypothetical waste burning plant of the same output level (as the real waste burning plant had a much lower output than the natural gas burning plant). The emergy analysis simultaneously considered all the factors such as the sustainability, renewability, environmental impacts, and economic issues. Some important findings and conclusions are listed below:

1) The transformity of electricity generated by the BNGPP and AMSWPP were 1.39 times more than that of the HMSWPP. It meant that to generate a unit of electricity output from the BNGPP and AMSWPP more emergy was required compared to the HMSWPP. Moreover, the results demonstrated that by increasing the efficiency of electricity output in an MSWPP, the transformity was decreased.

2) The percent renewability of the BNGPP, AMSWPP, and HMSWPP were 4.58, 46.83, and 64.73, respectively; therefore the PR of the HMSWPP was significantly more than that of the other two systems.

3) The EYR of the BNGPP, AMSWPP, and HMSWPP were 1.05, 1.88, and 2.84, respectively. The higher the value of the EYR, because of the amount of purchased inputs, the better the economic benefit.

4) The ELR of the BNGPP, AMSWPP, and HMSWPP were 20.82, 1.14, and 0.54, respectively. The ELR of the BNGPP was higher than the others, where such high ELR was achieved because of the considerable portion of fossil fuel (natural gas) input.

5) The ESI of the BNGPP, AMSWPP, and HMSWPP were 0.05, 1.66, and 5.2, respectively. The highest ESI belonged to the HMSWPP so that this power plant has the better sustainability.

6) By considering the environmental impacts and the capability of power plant to utilize the local resources, a large scale MSWPP with high electricity output capacity is a better choice.

CRediT authorship contribution statement

Shima Yazdani: Conceptualization, Methodology, Formal analysis, Investigation, Resources. Erfan Salimipour: Writing - original draft, Writing - review & editing, Visualization. Mojtaba Saei Moghaddam: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Erfan Salimipour.

References

Ahmadi, G.R., Toghaie, D., 2016. Energy and energy analysis of montazeri steam power plant in Iran. Renew. Sustain. Energy Rev. 56, 454–463.
Bargigli, S., Cigolotti, V., Pierini, D., Moreno, A., Iacobone, F., Ulgiati, S., 2010. Cogeneration of heat and electricity: a comparison of gas turbine, internal combustion engine, and MCFC/GT hybrid system Alternatives. J. Fuel Cell Sci. Technol. 7 (1), 011019.
Bergquist, D.A., Cavalett, O., Rydberg, T., 2011. Participatory emergy synthesis of integrated food and biofuel production: a case study from Brazil. Environ. Dev. Sustain. 14 (2), 167–182.
Brown, M.T., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9 (1–2), 51–65.
Brown, M.T., Ulgiati, S., 2002. Energy evaluations and environmental loading of electricity production systems. J. Clean. Prod. 10 (4), 321–334.
Brown, M.T., Ulgiati, S., 2010. Updated evaluation of energy and emergy driving the geobiosphere: a review and refinement of the emergy baseline. Ecol. Model. 221, 2501–2508.
Brown, M.T., Ulgiati, S., 2016. Assessing the Global Environmental Sources Driving the Geobiosphere: A Revised Emergy Baseline. Ecological Modelling, Bruunner, P.H., Rechberger, H., 2015. Waste to energy – key element for sustainable waste management. Waste Manag. 37, 3–12.
Campbell, D.E., 1998. Emergy analysis of human carrying capacity and regional sustainability: an example using the state of Maine. Environ. Monit. Asses. 51 (1–2), 531–569.
Campbell, D.E., 2016. Emergy baseline for the Earth: a historical review of the science and a new calculation. Ecol. Model. 339, 96–125.
Chen, T.C., Lin, C.-F., 2008. Greenhouse gases emissions from waste management practices using Life Cycle Inventory model. J. Hazard Mater. 155 (1–2), 23–31.
Cheng, C.-F., Cheng, K.-T., 2017. Evaluation of the sustainability of Hakka villages in the Lui–Tai area of China via emergy analysis. Environ. Dev. Sustain. 20 (6), 2831–2856.
Cheng, H., Hu, Y., 2010. Municipal solid waste (MSW) as a renewable source of energy: current and future practices in China. Bioresource. Technol. 101 (11), 3816–3824.
Cristiano, S., Gonella, F., 2019. To build or not to build? Megaprojects, resources, and environment: an energy synthesis for a systemic evaluation of a major highway expansion. J. Clean. Prod. 223, 772–789.
Dijkema, C.P.J., Reuter, M.A., Verhoef, E.V., 2000. A new paradigm for waste management. Waste Manag. 20 (8), 633–638.
Esen, M., Yuksel, T., 2013. Experimental evaluation of using various renewable energy sources for heating a greenhouse. Energy Build. 65, 340–351.
Esen, H., Inalii, M., Esen, M., 2006. Technoeconomic appraisal of a ground source heat pump system for a heating season in eastern Turkey. Energy Convers. Manag. 47 (9–10), 1281–1297.
Esen, H., Inalii, M., Esen, M., 2007. A techno-economic comparison of ground-coupled and air-coupled heat pump system for space cooling. Build. Environ. 42 (7), 1955–1965.
Fei, W., Wen, Z., Huang, S., De Clercq, D., 2018. Mechanical biological treatment of municipal solid waste: energy efficiency, environmental impact and economic feasibility analysis. J. Clean. Prod. 178, 731–739.
Hossaini, N., Hzewag, K., 2013. Energy accounting for regional studies: case study of Canada and its provinces. J. Environ. Manag. 118, 177–185.
Islam, K.M.N., 2018. Municipal solid waste to energy generation: an approach for enhancing climate co-benefits in the urban areas of Bangladesh. Renew. Sustain. Energy Rev. 81, 2472–2480.
Khayamabashi, E., 2016. Current Status of Waste Management in Iran and Business Opportunities.
Khoronen, J., Okkonen, L., Niuateran, V., 2003. Industrial ecosystem indicators directed and indirect effects of integrated waste- and by-product management and energy production. Clean Technol. Environ. Policy 6 (3).
Leckner, B., 2015. Process aspects in combustion and gasification Waste-to-Energy (WtE) units. Waste Manag. 37, 13–25.
Lee, J.M., Braham, W., 2019. Right-sizing cities for maximum power: urban form parameters for New York city and the greater Philadelphia region. Sustainability 11 (8).
Li, C., Gillum, C., Toupin, K., Park, Y.H., Donaldson, B., 2016. Environmental performance assessment of utility boiler energy conversion systems. Energy Convers. Manag. 120, 135–143.
Liamsanguan, C., Gheewala, S.H., 2008. LCA: a decision support tool for environmental assessment of MSW management systems. J. Environ. Manag. 87 (1), 132–138.
Liamsanguan, C., Gheewala, S.H., 2008. The holistic impact of integrated solid waste management on greenhouse gas emissions in Phuket. J. Clean. Prod. 16 (17), 1865–1871.
Liu, G., Yang, Z., Chen, B., Zhang, Y., Su, M., Zhang, L., 2013. Emergy evaluation of the urban solid waste handling in Liaoning Province, China. Energies 6 (10), 5486–5506.
Liu, J., Dong, Y., Dong, L., Yang, Z., Zhang, Y., Ulgiati, S., 2017. An emergy-LCA analysis of municipal solid waste management. Resour. Conserv. Recycl. 120, 131–143.
Lombardi, L., Carnevale, E., Corti, A., 2015. A review of technologies and performances of thermal treatment systems for energy recovery from waste. Waste Manag. 37, 26–44.
Marchettini, N., Ridolfi, R., Rustici, M., 2007. An environmental analysis for comparing waste management options and strategies. Waste Manag. 27 (4), 562–571.
Marchi, M., Pulseli, F.M., Mangiavacchi, S., Menghetti, F., Marchettini, N., Bastianoni, S., 2017. The greenhouse gas inventory as a tool for planning integrated waste management systems: a case study in central Italy. J. Clean. Prod. 142, 351–359.
Münster, M., Meibom, P., 2011. Optimization of use of waste in the future energy system. Energy 36 (3), 1612–1622.
Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley and Sons, New York.
Odum, H.T., 2000. Handbook Of Emergy Evaluation (Folios #2): A Compendium Of Data For Emergy Computation Issued In A Series Of Folios. Center for Environmental Policy: Environmental Engineering Sciences, University of Florida, Gainesville, Fl.
Pan, H., Ceng, Y., Jiang, P., Dong, H., Sun, L., Wu, R., 2018. An emergy based
sustainability evaluation on a combined landfill and LFG power generation system. Energy 143, 310–322.
Rajaeifar, M.A., Ghanavati, H., Dashti, B.B., Heijungs, R., Aghbashlo, M., Tabatabaei, M., 2017. Electricity generation and GHG emission reduction potentials through different municipal solid waste management technologies: a comparative review. Renew. Sustain. Energy Rev. 79, 414–439.
Rezaei, Mahdi, Ghobadian, Barat, Seyed Hashem Sanadi, Karimi, S., 2018. Electric power generation from municipal solid waste: a techno economical assessment under different scenarios in Iran. Energy 152, 46–56.
Rogoff, M., 2013. ‘Sustainable materials management’: a new international solid waste paradigm. Waste Manag. Res. 31 (12), 1187–1189.
Santos, R.E.d., Santos, I.F. S.d., Barros, R.M., Bernal, A.P., Tiago Filho, G.L., Silva, Ed.G.B.d., 2019. Generating electrical energy through urban solid waste in Brazil: an economic and energy comparative analysis. J. Environ. Manag. 231, 198–206.
Seadon, J.K., 2010. Sustainable waste management systems. J. Clean. Prod. 18 (16–17), 1639–1651.
Siracusa, G., La Rosa, A.D., Palma, P., La Mola, E., 2007. New frontiers for sustainability: emergy evaluation of an eco-village. Environ. Dev. Sustain. 10 (6), 845–855.
Song, Q., Wang, Z., Li, J., 2013. Environmental performance of municipal solid waste strategies based on LCA method: a case study of Macau. J. Clean. Prod. 57, 92–100.
T. U. N. E. P. (UNEP), 2004. Waste Management Planning—An Environmentally Sound Approach for Sustainable Urban Waste Management—An Introductory Guide for Decision-Makers. United Nations Publications, Nairobi, Kenya ([Online]. Available).
Tabata, T., 2013. Waste-to-energy incineration plants as greenhouse gas reducers: a case study of seven Japanese metropolises. Waste Manag. Res. 31 (11), 1110–1117.
Tan, S.T., Hashim, H., Lim, J.S., Ho, W.S., Lee, C.T., Yan, J., 2014. Energy and emissions benefits of renewable energy derived from municipal solid waste: analysis of a low carbon scenario in Malaysia. Appl. Energy 136, 797–804.
Tarr, J.A., 1996. The Search For the Ultimate Sink: Urban Pollution In Historical Perspective (Technology And the Environment) (Technology and the Environment). University of Akron Press, p. 419.
Vlaskin, M.S., 2018. Municipal solid waste as an alternative energy source. Proc. IME J. Power Energy, 0957650918762022.
Wang, X., et al., 2014. Efficiency and sustainability analysis of biogas and electricity production from a large-scale biogas project in China: an energy evaluation based on LCA. J. Clean. Prod. 65, 234–245.
Wang, Y., et al., 2018. Investigating Impact of Waste Reuse on the Sustainability of Municipal Solid Waste (MSW) Incineration Industry Using Emergy Approach: A Case Study from Sichuan Province, China. Waste Management, Wilfart, A., Prudhomme, J., Blancheton, J.-P., Aubin, J., 2013. LCA and emergy accounting of aquaculture systems: towards ecological intensification. J. Environ. Manag. 121, 96–109.
Yang, J., Chen, B., 2014. Emergy analysis of a biogas-linked agricultural system in rural China—a case study in Gongcheng Yao Autonomous County. Appl. Energy 118, 173–182.
Yang, J., Chen, B., 2016. Emergy-based sustainability evaluation of wind power generation systems. Appl. Energy 177, 239–246.
Yazdani, S., Deymi-Dashtebayaz, M., Salimipour, E., 2019. Comprehensive comparison on the ecological performance and environmental sustainability of three energy storage systems employed for a wind farm by using an emergy analysis. Energy Convers. Manag. 191, 1–11.
Zhang, X., Jiang, W., Deng, S., Peng, K., 2009. Emergy evaluation of the sustainability of Chinese steel production during 1998–2004. J. Clean. Prod. 17 (11), 1030–1038.
Zhang, M., Wang, Z., Xu, C., Jiang, H., 2012. Embodied energy and emergy analyses of a concentrating solar power (CSP) system. Energy Pol. 42, 232–238.
Zhou, Z., et al., 2018. Environmental performance evolution of municipal solid waste management by life cycle assessment in Hangzhou, China. J. Environ. Manag. 227, 23–33.