Advanced technology of municipal solid waste conversion for a circular economy

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Abstract. One of the most important environmental problems of the big urban areas is represented by the large volume of waste resulted from different human activities. In the last decades, different technologies have been developed to resolve this significant issue, and the most representative is the conversion of municipal solid waste (MSW) in different types of by-products. The first part of this paper presents the current state of plasma conversion technology that can be used for processing waste, and also, its potential in the construction sector which could be taken advantage of the by-products (syngas and slag) resulted from the plasma gasification of municipal solid waste (MSW), to enhance energy-efficiency in this domain. In the second part of the paper, there are analyzed different technologies for managing and processing municipal solid waste (MSW), which can be used nowadays, and the parameters, related to the costs, the period of use, the energy consumption and the environmental impact. All these aspects are compared with those of plasma conversion technology. The plasma conversion system can be commercialized successfully, and its costs can be reduced by generating income in the form of by-products and added-value in producing performant products in a circular economy.

1. Introduction

In the last decades, all over the world, it was observed that one of the most important environmental problems of the big urban areas is represented by the large volume of waste that is resulted from different human activities, domestic and industrial. Eurostat shows that in 2016 only in Romania were generated 9012 kg per inhabitant of waste and in the European Union on average 4968 kg per inhabitant of waste [1]. According to the World Bank Group statistics, more than 2000 million tones of waste were generated worldwide in 2018, and it is expected to increase to more than 3.4 billion tons by 2050, as shown in figure 1 [2].
To reduce this alarming amount of municipal solid waste that goes to landfills, the available solutions are re-use, recycle and usage of waste to energy technologies [3].

Recycling is an alternative to conventional waste management. It is the process of transforming waste into new materials and objects that can help to lower greenhouse gas emissions [4].

Waste to energy concept is the process of converting waste into energy in the shape of electricity, heat and/or synthetic fuels [5].

2. The principal thermochemical technologies for treating municipal solid waste

2.1. Incineration and co-processing

Incineration is a combustion process that transforms waste into ash, exhaust gases and heat, reducing the initial volume to almost 5%. Incineration sterilizes the dangerous wastes, generating at the same time thermal energy that can be in the form of heat (hot water or steam), electricity or both [6].

In modern waste management incineration has the role of treating the waste that can’t be recycled with the following advantages [6, 7]:

- all municipal solid waste, as well as some hazardous and industrial waste, can be disposed of, unsorted;
- municipal solid waste volume is reduced to 5%, and is mainly composed of ash which can be recycled as a filler in road construction;
- well-known process, installed worldwide, with high availability and stable operating conditions;
- if cogeneration of heat and electricity is used, or only heat results in a high-efficiency energy recovery up to 85%;
- ash and other waste materials resulted are inert;
- by incinerating waste, the release of methane is prevented [8].

Disadvantages:

- Incinerators demand substantial financial investments and a long time to recover the initial investment, generating a long-term lock-in. Incinerator lifetimes normally range from 25–30 years. Substantial financial investments.
- A large quantity of toxic fly ash and exhaust gas, which must be disposed of by storage at a suitable warehouse (approximately 2-5% of the weight of the input waste) [8].
- NO$_x$ and other gases and small particles.
- Bottom Ash with medium toxicity with concerns of releasing heavy metals to the environment [9].
- Very often the local communities are hostile with the idea of having waste incinerating plants near them, this is called Not in My Back-Yard phenomenon. A study made in Massachusetts, US, showed that the property close to the incinerator plant devaluated with 10% [10].

In the European Union, approximately 29% of the municipal solid waste generated was incinerated in 2017, compared to Sweden, Denmark, and Finland that incinerated more than 50% of their municipal solid waste [11].

To ensure that incineration plants don’t release in the air major CO$_2$ and other Greenhouse Gas Emissions the European Union has created standards for incineration emissions shown in table 1, table 2, table 3 and table 4, and also for discharging wastewater that was used in emission cleaning showed in table 5 [6, 12].

**Table 1.** European Union limits for hazardous substance emission from waste-to-energy incinerators burning solid fuels [6, 12].

| Pollutant | Values in mg/Nm$^3$ according to Plant Output |
|-----------|-----------------------------------------------|
|           | 50 - 100 MWth | 100 - 300 MWth | >300 MWth |
| SO$_2$    | 850 or rate of desulfurization > 90% | 850 to 200 (linear decrease from 100 to 300 MWth) or rate of desulfurization > 92% | 200 or the rate of desulfurization >95% |
| NO$_x$    | 400            | 300            | 200        |
| Dust      | 50             | 30             | 30         |

**Table 2.** European Union limits for hazardous substance emission from waste-to-energy incinerators burning biomass [6, 12].

| Pollutant | Values in mg/Nm$^3$ according to Plant Output |
|-----------|-----------------------------------------------|
|           | 50 - 100 MWth | 100 - 300 MWth | >300 MWth |
| SO$_2$    | 200            | 200            | 200        |
| NO$_x$    | 350            | 300            | 300        |
| Dust      | 50             | 30             | 30         |

**Table 3.** European Union limits for hazardous substance emission from waste-to-energy incinerators burning liquid fuels [6, 12].

| Pollutant | Values in mg/Nm$^3$ according to Plant Output |
|-----------|-----------------------------------------------|
|           | 50 - 100 MWth | 100 - 300 MWth | >300 MWth |
| SO$_2$    | 850            | 850 to 200 (linear decrease from 100 to 300 MWth) | 200        |
| NO$_x$    | 400            | 300            | 200        |
| Dust      | 50             | 30             | 30         |
Table 4. European Union limits for hazardous substance emission from waste-to-energy incinerators burning solid, liquid or biomass fuels [6, 12].

| Pollutant | Limit (mg/Nm$^3$ except dioxins/furans in ng/Nm$^3$) |
|-----------|-----------------------------------------------------|
| Cd+Tl     | 0.05                                                |
| Mercury   | 0.05                                                |
| Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V | 0.05                                              |
| Dioxins and Furans | 0.1                                               |

Table 5. European Union emission limit values for discharges of wastewater from the cleaning of exhaust gases [6, 12].

| Polluting substances | Emission limit values expressed in mass concentrations for unfiltered samples |
|----------------------|--------------------------------------------------------------------------------|
| Total suspended solids as defined by Directive 91/271/EEC | 95 % 100% |
| Mercury and its compounds expressed as mercury (Hg) | 0.03 mg/l 30 mg/l 45 mg/l |
| Cadmium and its compounds expressed as cadmium (Cd) | 0.05 mg/l |
| Thallium and its compounds expressed as thallium (Tl) | 0.05 mg/l |
| Arsenic and its compounds expressed as arsenic (As) | 0.15 mg/l |
| Lead and its compounds expressed as lead (Pb) | 0.2 mg/l |
| Chromium and its compounds expressed as chromium (Cr) | 0.5 mg/l |
| Copper and its compounds expressed as copper (Cu) | 0.5 mg/l |
| Nickel and its compounds expressed as nickel (Ni) | 0.5 mg/l |
| Zinc and its compounds expressed as zinc (Zn) | 1.5 mg/l |
| Dioxins and furans, defined as the sum of the individual dioxins and furans | 0.3 mg/l |

2.2. Pyrolysis

Pyrolysis is a thermal method of pre-treatment, which can be applied to convert organic waste into a medium calorific gas, into liquid and a carbonized fraction aiming at the separation or binding of chemical compounds to reduce emissions and leachate [13, 14]. The word pyrolysis comes from the Greek language, pyro means “fire” and lysis means “separating” [15]. Usually, after pyrolysis results volatile products and solid residue high in carbon named char. Extreme exposure to pyrolysis leaves mainly carbon as residue, this process is called carbonization [16].
Advantages:
• better retention of heavy metals in carbonized residues [17];
• a smaller quantity of emission gases than in incineration [17];
• hydrochloric acid can be retained in or distilled from the solid residue [17, 18];
• all resulted residues are inert [18].

Disadvantages:
• waste must be sorted and shredded before entering the pyrolysis reactor to prevent the blocking of the feeding and transport flow [17];
• resulted oils and tars could have dangerous and carcinogenic elements [17];
• relative high cost [17];
• fuel supply is required at least during start-up [17].

2.3. Plasma gasification
Gasification is a method of heat treatment, which can be applied to convert organic waste into a medium calorific gas, recyclable products, and residues. Gasification is normally followed by combustion of the gases produced, in a furnace and internal combustion engines or simple gas turbines after a proper purification of the gas produced [14, 19].

The principal difference between gasification and pyrolysis is that by gasification the fixed carbon is also gasified [13, 19]. For commercial use, the available gasification technologies are counter-current fixed bed, co-current fixed bed, fluidized bed, entrained flow, plasma, and free radical [20, 21].

Plasma gasification is a thermal process that uses plasma to transform organic compounds into synthesis gas (syngas) which mainly contains H₂, CO, and CH₄, that can be used for direct combustion or raw material [22].

Plasma, also known as the fourth state of matter, is formed by a strong electric current that passes through a gas who is ionized and converts organic compounds into syngas, with slag as a by-product [22].

Plasma is formed by the interaction between the electric current and the gas which is ionized and causes the temperature of the gas to increase significantly to more than 5500°C, almost as hot as the sun’s surface [23].

Plasma torches can be supplied with various gases, air, oxygen, nitrogen, argon, and others. This flexibility allows the plasma unit to be adapted for various applications [24].

Figure 2. Plasma torch schematic [24].
Plasma gasification technology is a highly efficient process of heating the waste that is introduced in the plasma reactor at an extremely high temperature until they dissociate resulting in primarily chemical elements, the equipment can operate with minimal maintenance in a different industrial environment.

The plasma torches offer a high level of flexibility for plasma reactors, as it allows temperature control, regardless of the flow of waste or oxygen in this process [25].

The main benefits of the plasma gasification are:

- high reliability – more than 500,000 hours of continuous operation in commercial use [26];
- available in a wide range of powers input, from 80 to 2,400 kw [26];
- input power can be adjusted to meet the process requirements;
- long electrode life [26];
- auto stabilization and non-transferred arc (figure 3) [27];
- process gases can be air, oxygen, nitrogen, etc [28];
- long-life electrode [29];
- the syngas with very low in NOx, SOx, dioxins, and furans [30];
- high reliability - plasma torches have no moving parts, consumables are quickly replaced by maintenance personnel

Plasma gasification is clean and efficient of converting different waste into energy in a responsible way towards the environment [30 - 32].

Plasma gasification process breaks the molecular structure of any carbon-contained materials - such as solid municipal waste, tires, hazardous waste, biomass, river sediment, coal, and petroleum coke and converts them into syngas, which can be used to generate energy, liquid fuels or other sustainable energy sources [30, 31].

Gasification takes place in a low oxygen environment so that raw materials are vaporized, not incinerated [30, 32].

![Figure 3. Schematic of a non-transferred arc discharge [27].](image)

Due to the high operating temperatures in the plasma gasification reactor, we can observe from an environmental point of view that:

- no ash that requires treatment or disposal in a landfill occurs [33];
- metals and non-combustible inorganic materials are melted and captured in a slag medium, which can be used as a construction aggregate [31];
- the plasma gasification plant has very low emissions of NOx, SOx, dioxins, and furans (figure 4) [30, 31];
- in the CO2 plasma gasification process can be captured and used for various industrial purposes [34].
3. Circular economy

It is known that the current economy consumes a significant amount of raw materials and non-renewable energy. Now, when humanity's negative influence on the environment is intensified, the implementation of an efficient circular economy is a highly debated topic internationally.

The circular economy focuses on eliminating waste by creating a closed-loop system (figure 5) that involves reusing, refurbishing, recycling, reducing the consumption of valuable resources and the production of waste, pollution and greenhouse gases such as CO₂, NOₓ, SOₓ, CH₄, and others [35-37].

To achieve a circular economy, it is necessary to recycle materials from waste as much as possible to have this closed-loop. For non-recyclable, hazardous and medical waste, an important role goes to waste-to-energy technologies, such as plasma gasification, that converts waste into energy and other inert by-products that can be utilised in construction or other fields, avoiding this way landfill disposal and reducing greenhouse gas emissions [38, 39].

This closed-loop demands primarily reusing, remaking and recycling. Another important aspect is that waste disposal should be eliminated as much as possible, and if not, it must be properly managed to ensure safety for human health and the environment.

In this context, the applications of life cycle assessment (LCA) of waste management plays an important role, and these can appear as buying bespoke LCA services; paying for staff training in this direction. These actions can be viable for the economy of large companies. The strategy is designed and
can be implemented taking into account the basis of the systematic application or it can be implemented ad-hoc when it is necessary [39].

While reusing, remaking and recycling have an important role, they will never solve all the problems with waste. Numerous packaging wastes simply cannot be recycled without degradation, such as multilayer or metallized plastics, and laminates incorporating foils and fibre. Even with traditional methods of recycling, it is needed a process to recover materials that cannot accomplish their functions and finally become waste [37].

Usually, the main outlet for wastes is into landfill sites. Other choices exist, incineration and pyrolysis, but of all achievable options, exclusively plasma gasification can accomplish circular economy sustainability. Incineration produces a large quantity of ash, which is usually toxic, along with complex exhaust that must be treated to accomplish emissions regulations [7].

As the industry progressively sources of plastic from renewable materials, emissions become significantly close to zero net carbon. Also, fossil fuel usage is balanced by producing clean energy with plasma gasification. Energy efficiency is achieved when syngas is used to power combined cycle turbines. The combined cycle means that a gas-fired turbine is used to produce electricity using syngas, and from this process occurs high-temperature which is then used to produce steam to engaged a second turbine which produces more electricity [32].

The availability of plasma gasification technologies will reduce the need for fuel imports, reducing waste collection, and transform waste into clean energy. Savings in fuel imports will provide means to enhance waste collection to magnify the clean energy production from municipal solid waste using plasma gasification [27].

From an economic point of view, how the regulatory framework and its enforcement are applied can be the principal hindrance. On the other hand, the implementation of local economic tools has important premises as good management skills, innovation, and last but not least, environmental awareness. The instruments at the local level can take the form of tax modulation or taxes, waste pricing, refunds, and product levies. By using these applications, there are following the environmental indicators, like stimulated good behaviour, and sharing by using the voluntary instrument [39].

4. Conclusions
As we realize that reusing, remaking and recycling are insufficient to achieve our sustainability aspirations, plasma gasification stands out as the most promising municipal solid waste treatment solution.

Considering all the applications of plasma conversion for waste to value processing, the potential environmental benefits could be enormous. Public and/or private companies could build waste treatment units having substantial financial benefits and also improving the actual waste collection and treating infrastructure.

Plasma conversion systems are the future in waste management because they have a considerable low impact on the environment, having the lowest emissions from all waste treatment technologies available at the moment. Another important aspect of this technology is that it can treat medical and hazardous waste, resulting in syngas, metals and inert slag.

Even though there are some conflicts between different scientists and governmental environmental strategy makers, plasma gasification has all the advantages for a circular economy.

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