15 An Overview of the Technological Applicability of Plasma Gasification Process

Spyridon Achinas

Abstract

Recent increased environmental and political pressures, the unstable perspective of the fuel prices, and the fossil-resource-based energy have risen the industrial interest into the energy that can be produced from waste and have enhanced the technological findings in waste-to-energy sector. Sustainable waste treatment is an essential element in efforts to improve sustainability. Plasma gasification is considered an alternative for the abatement of municipal waste and has been demonstrated for the treatment of various wastes more in Japan, Canada, and the USA than in Europe. The goal of this mini-review is to brief the plasma-based gasification technology. This study includes a technological overview of the PG process, a survey of existing PG facilities, a comparison with other thermal techniques, and an identification of its environmental impacts.

Keywords

Plasma gasification · Waste management · Sustainability · Green energy · Thermal technology

Highlights

- We summed up the plasma gasification technology.
- Survey of waste treatment facilities worldwide using plasma gasification.
- Technical and environmental comparison with other thermal technologies.
- Barriers on the plasma gasification application are addressed.

S. Achinas (✉)
Faculty of Science and Engineering, University of Groningen, Groningen, The Netherlands
e-mail: s.achinas@rug.nl

P. Singh et al. (eds.), *Contemporary Environmental Issues and Challenges in Era of Climate Change*, https://doi.org/10.1007/978-981-32-9595-7_15

15.1 Introduction

Recent increased environmental and political pressures, the unstable perspective of the fuel prices, and the fossil-resource-based energy have raised the industrial interest into the energy that can be produced from waste and have enhanced the technological findings in waste-to-energy sector (Tendler et al. 2005; Vaish et al. 2016, 2019). The disposal of waste remains a crucial issue, as stockpiling or landfilling of garbage has a negative impact. The European countries have to improve their waste management policy according to the Waste Directive Framework (Directive 2008/98/EC) for sustainable development, but the lack of project investments is apparent, and the problem persists.

Plasma gasification (PG) is a thermochemical process whereby wastes (produced or currently being landfilled) are converted into valuable energy in the form of gaseous fuel (syngas) that can be used for heat, power, or biofuel production. PG technology aims to the destruction of waste using high temperature (Fauchais 2007). Several companies through their representative solutions have facilities in various stages of permitting, constructing, or planning worldwide that could potentially destruct different wastes. However, PG facilities globally are currently operating under stringent regulations with different wastes, and it is expected that the facilities equipped with the most advanced air pollution control systems will be able to meet or exceed the regulatory restrictions in Europe.

The goal of this review is to provide a technical overview of the potency of the PG application. This assessment includes a technological analysis of the PG process, a survey of existing PG facilities, an assessment of the environmental aspects of PG technology, a characterization of useful end products, and a generic approach of PG economics incorporating operating costs and revenue potential from PG operations.

15.2 Plasma Gasification Technology

15.2.1 Feedstock

In a typical plasma gasifier, the feedstock enters from the top to the bottom of the furnace. It was found that PG technology has considerably expanded in the areas of municipal solid waste (MSW), fly ash, and hazardous and industrial waste (Leal-Quirós 2004; Serbin and Matveev 2010). Although the demonstration of PG to hazardous feedstocks is limited worldwide, no significant technical barriers to the application of this technology in processing hazardous seem to exist. This is particularly evident in the significant expansion of PG use, including feedstocks that are more heterogeneous than MSW, automotive shredder residue (ASR), tires, and mixed waste (An'Shakov et al. 2007; Dave and Joshi 2010).

15.2.2 Thermochemical Reactions

Gasification process includes various chemical reactions that are strongly dependent on the reactor conditions (temperature, gasification agent, etc.). While gasification processes vary considerably, typical gasifiers operate at temperatures between 700 and 800 °C (Basu 2010). The intrinsic gasification reactions are given in Eqs. 15.1, 15.2, 15.3, 15.4, 15.5, 15.6, 15.7, and 15.8 (Higman and Van Der Burgt 2008):

$$C + CO_2 = 2CO \qquad \Delta Ho = +172\,kJ \tag{15.1}$$

$$C + H_2O(g) = CO + H_2 \qquad \Delta Ho = +130\,kJ \tag{15.2}$$

$$C + 2H_2O(g) = CO2 + 2H_2 \quad \Delta Ho = +88\,kJ \tag{15.3}$$

$$C + 2H_2 = CH_4 \qquad \Delta Ho = -71\,kJ \tag{15.4}$$

$$CO + H_2O(g) = CO_2 + H_2 \qquad \Delta Ho = -42\,kJ \tag{15.5}$$

$$CO + 3H_2 = CH_4 + H_2O(g) \quad \Delta Ho = -205\,kJ \tag{15.6}$$

$$C + 1/2\,O_2 = CO \qquad \Delta Ho = -109\,kJ \tag{15.7}$$

$$C + O_2 = CO_2 \quad \Delta Ho = -309\,kJ \tag{15.8}$$

It is notable that synthesis gases for liquid fuels and chemicals are composed of gaseous mixtures of CO_2 and hydrogen. The carbon monoxide–hydrogen ratio is varied under process conditions and is typically related to the range of products. In contrast, pyrolysis does not include a reactive step, and its gaseous yield is lower and cannot be used for direct fuel or chemical synthesis without further processing (De Souza-Santos 2008).

PG operates at elevated temperatures to break the feedstock to molecules (Higman and Van Der Burgt 2008). Plasma is generated by heating a gas to very high temperatures where the molecules and atoms are ionized and toxic compounds such as dioxins are completely decomposed to harmless chemical elements.

15.2.3 Plasma Gasification Unit

A PG facility includes a preprocessing unit (i.e., shredder), a feeding system, an equipment to process the by-product (slag) derived from the plasma furnace, a syngas treatment system, and a monitoring and control system. The main device of a PG facility is the plasma-based furnace and specifically the plasma torches (Bratsev et al. 2006a, b).

15.2.3.1 Plasma Gasification Vessel

The gasification vessel is the main design component in the PG plant. The choice of reactor type and torch configuration relies on the process conditions and the feedstock type (Bratsev et al. 2006a, b; Hrabovsky et al. 2006). Plasma gasification reactor (PGR) is a vertical furnace that is similar to that used in the foundry facilities for the melting of metallic materials. PGR can afford high internal temperatures and corrosive environment. The gasification reactions will convert the organic substance of the MSW feedstock into a syngas which exits the PGR, while the inorganic fraction will be transformed into a molten slag that exits the bottom. The PGR operates at elevated temperature in the lower part of the chamber, and oxygen and/or steam are injected into the process.

Two configurations of plasma gasifier (Fig. 15.1) are commonly used in industrial scale and are related to the placement location of the plasma torches. The typical configuration of a PG furnace is that the processed waste feedstock is fed into the furnace from the top. The electrodes which are responsible for the arc generation with the help of current extend into the lower part of the furnace, the so-called melting chamber. Gas enters the furnace through the torches and is ionized due to the high-temperature (up to 6000 °C) plasma jets applied. Various gases (O_2, air, N_2, CO_2, $H_20_{(g)}$) can be used with air to be the most cost-effective. Additional gas (most common air or stream) is introduced through the nozzles to control the gasification reactions. An alternative plasma gasification technique used in industrial scale combines the plasma technology and the common gasification. This technique is not considered exactly as a thermal PG technology but as a thermal plasma treatment of gases leaving the reactor. In this case, the plasma arc destructs the tars, toxins, and furans included in the syngas at the exit of the plasma gasifier (Fourcault et al. 2010).

The combined process is able to produce a clean synthetic gas (main components H_2 and CO) that can be used to generate electricity in combined heat power (CHP) gas engines or can substitute natural gas. The multistage process unit combines gasification and plasma conditioning. A main component of the process is the thermal aftertreatment of the syngas by means of generated plasma. It is necessary for

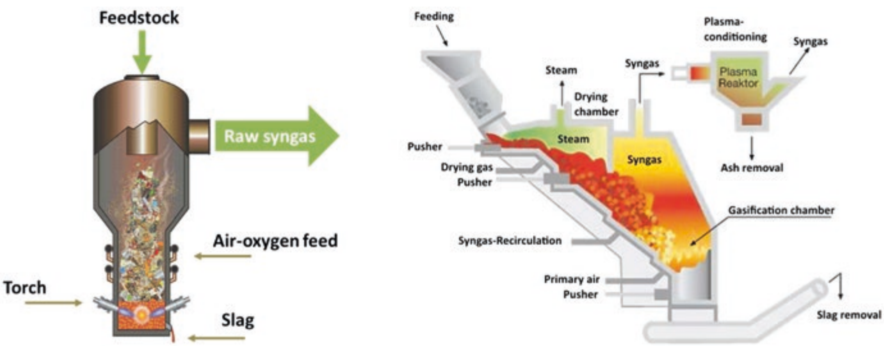

Fig. 15.1 Plasma-assisted gasifier from Alter NRG (left) and combined plasma gasifier from Europlasma (right) (Alter NRG; CHO-Power)

cracking and transformation of macromolecular hydrocarbons. Plasma torches are only used for the thermal cracking of the syngas and for slag vitrification.

15.2.3.2 Post-Processing Unit

The gaseous product exits the furnace that can be used for energy and fuel production. The thermal energy resulting from the syngas can be exploited in a variety of ways. These include the steam generation for further electricity and heat production. The design of the posttreatment equipment used to clean the effluent gases is crucial for the viable operation of a PG plant. Advanced emission control systems are required to meet regulatory standards. Typical process equipment for the treatment of exhaust gases consists of particulate filters, wet scrubbers, or electrostatic precipitators. Syngas is cleaned in a multistage process, the number of stages being dependent on how clean the syngas needs to be for the particular utilization and conversion process specified in each specific project. These multistage elements can add considerably to the capital costs and incur significant operating costs for the disposal of secondary residues. They can also reduce the overall plant operational availability and, in some circumstances, lower revenues from energy sales.

15.3 Survey of PG Facilities Worldwide

A literature-based identification of existing PG facilities was conducted, and their basic characteristics are given in Table 15.1. Alter NRG is a company with extensive experience and has built several commercial installations in Japan, China, the United Kingdom, and India. PEAT International, SRL Plasma, and InEnTec have also constructed facilities with a capacity up to 10 tpd using industrial, medical, and hazardous wastes. The pending PG projects were not identified in the analysis.

15.4 Products of PG Facility

The most crucial product from alternative conversion processes is the gaseous product so-called synthetics gas or syngas (Fig. 15.2). The syngas is a valuable gas with the main components CO and hydrogen. This synthetic gas can be used for fuel production, heat, or energy (Ducharme and Themelis 2010). The commercial applications of synthesis gas are split between chemical production, fuel production, and energy (heat/power) production. The percentage of PG facilities producing electrical power and utilizing post-combustion products has risen significantly due to demand and deregulation of electricity markets as well as accumulation of wastes.

Other potential products of PG processes include chemicals and fuels which can be stored and sold when the market price is higher. Inorganic materials in the feedstock are melted into slag, which is nonhazardous and can be used in a variety of applications, such as road construction and roofing materials. Marketing feasibility depends on the cleanliness, quantity, and packaging of the slag. Metal sources are also generated from the plasma gasification process. The metals produced can be

Table 15.1 Plants for waste treatment by plasma technique currently in operation around the world and plant projects for the next years

Technology supplier	Country	City, province	Owner	Capacity (tpd)	Feedstock	Output	Commission
Alter NRG	Japan	Utashinai, Hokkaido	Hitachi Metals	220	MSW, ASR	Power	2003
Alter NRG	Japan	Mihama-Mikata	Hitachi Metals, Hitachi	24	MSW, WW sludge	Heat	2002
Alter NRG[a]	Japan	Yoshi	Hitachi Metals, Hitachi	151	MSW		1999
Alter NRG	India	Nagpur	SMS Envocare	68	Hazardous waste	Power	2008
Alter NRG	India	Pune	SMS Envocare	68	Hazardous waste	Power	2009
Alter NRG	China	Wuhan, Hubei	Wuhan Kaidi	150	Biomass	Biofuel	2012
Alter NRG	China	Shanghai	GTS Energy	30	Medical waste, incinerator fly ash	Slag	2014
Alter NRG[a]	USA	Madison, Pennsylvania	Alter NRG	48	Over 100 tested	Syngas	1990
Advanced Plasma Power	United Kingdom	Wiltshire	NG, Stonehouse, PR, CNG Services	300	Waste, biomass	Syngas, power	2008
Advanced Plasma Power[a]	United Kingdom	Swindon, Wiltshire	NG, Advanced Plasma Power, PE	22	RDF	bioSNG	2017
Advanced Plasma Power	United Kingdom	Energy Park Peterborough			Mixed waste	Power	2014
CHO-Power	France	Morcenx		200	Cardboard, wood, paper, tissues	Power, heat	2012
Bellwether RG	Romania	Brasov	Dunarea SA	240	Calorific waste	Power, heat	2008
InEnTec	Japan	Iizuka	Fuji Kaihatsu Ltd.	10	Industrial wastes	Power	2002
InEnTec[a]	Japan	Okinawa	Kawasaki		PCB oil and PCB-contaminated materials		2003

InEnTec[a]	USA	Kapolei	Asia Pacific Environmental Technologies		Medical waste	Power	2001
InEnTec[a]	Taiwan	Kuan Yin (Taipei)	Global Plasma Technology Limited	4	Medical waste, batteries, solvents, lab packs, mercury vapor lamps		
InEnTec	USA	Arlington	InEnTec Columbia Ridge LLC		MSW	Syngas, H_2	
InEnTec[c]	USA	Richland	InEnTec LLC	4	Hazardous waste		1996
InEnTec	USA	Richland	InEnTec LLC		Hazardous and nuclear waste; TSCA and PCB waste		1999
InEnTec	USA	Richland	Allied Technology Group, Inc.		Mixed hazardous and radioactive wastes		1999
InEnTec	Malaysia	Kuala Lumpur	Boeing Company/ BioPure Systems				
InEnTec	Japan	Harima	Kawasaki Plant Systems		Asbestos		
InEnTec	USA	Midland, Michigan	Dow Corning Corp.		Industrial by-products		
PyroGenesis[b]	Canada	Montreal	PyroGenesis	0.5–2.5	Mixed waste		2002
PyroGenesis	USA	US Navy	US Navy	7	Shipboard wastes		2004
PyroGenesis	USA	Hurlburt Field	Air Force Special Operations Command	10.5	MSW, hazardous wastes		2011
Plasco Energy Group[a]	Canada	Ottawa		85	MSW	Power	2007
SRL Plasma – PLASCON[a]	Australia		Nufarm Limited	0.8	Chlorophenols, phenoxies, toluene, dioxins/furans		1995

(continued)

Table 15.1 (continued)

Technology supplier	Country	City, province	Owner	Capacity (tpd)	Feedstock	Output	Commission
SRL Plasma – PLASCON[a]	Australia		BCD Technologies	1	Concentrated polychlorinated biphenyl (PCB) waste		1997
PEAT International[b]	China	Shanghai	Abada Plasma Technology Holdings	1.2	Medical waste, oil refinery sludge		2013
PEAT International[a]	Taiwan	Tainan		4	Waste and toxic waste such as incinerator fly ash, medical waste, inorganic sludges		2005
PEAT International[a]	USA	Lorton, Virginia		7	Defense department waste, medical waste		

Alter NRG, CHO-Power, PEAT, InEnTec, PyroGenesis Canada, Tetronics International, Advanced Plasma Power, Plasma Arc Technologies, Plasco Energy Group, Westinghouse Plasma, Europlama

[a]Demonstration

[b]Pilot

[c]Test facility

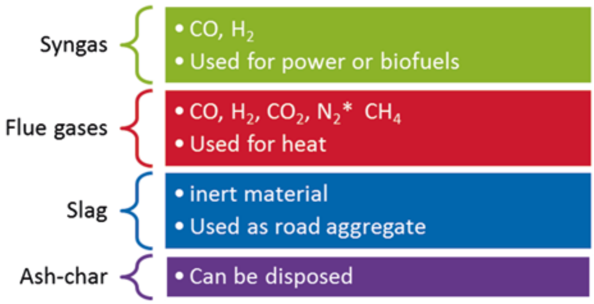

Fig. 15.2 Product range from plasma gasification operation

collected in molten form from subsequent processing in smelters. If the volume of metals is large enough to warrant separation, then the plant is configured to recapture metals. It is reported that slag derived from the vitrification of inorganic waste fraction has shown acceptable leachability limit and can be regarded as inert waste and therefore can be used as building components or disposed to a landfill.

15.5 Air Emissions from Plasma Gasification Operations

PG process is regarded as a promising technique to break down hazardous waste (i.e., medical waste) (Nema and Ganeshprasad 2002). It also displays lower environmental impacts in terms of air emissions and slag leachate toxicity as compared to other waste-to-energy processes, such as incineration (Hlína et al. 2006; Chang et al. 1996). However, empirical data on the environmental impacts of PG facilities are limited and depend on the local air permits and exhaust aftertreatment systems utilized at each facility. PG process has some emission advantages compared to conventional thermal treatment processes since it produces emissions far below the most stringent regulatory requirements. PG decomposes various types of wastes including low-strength radioactive waste to their elemental form. PG offers considerable environmental benefits with negative carbon footprint in comparison with other thermal energy technologies and has the highest landfill diversion rate of any available technology, making it very attractive to local authorities (Murphy et al. 2002). When compared to operations that utilize combustion of waste tires, it is generally accepted that PG technology will yield lower environmental risks and impacts in most areas. However, the information available is limited, due to the secrecy of full-scale PG facilities. Additionally, some older information on PG facilities may not be relevant due to recent advances in emission controls.

Air emissions may be the greatest environmental concern in PG operations. The output gases of plasma gasifiers contain a variety of air pollutants that must be eliminated prior to their release into the atmosphere. There are many strategies available for controlling emissions from PG process. The PG process differs in a number of key ways from common thermal processes, as the former generate intermediate gaseous products that can be converted into fuels or chemicals with almost no direct emissions. Information regarding output products of plasma gasification and problems that may be encountered is difficult to obtain as performance data from plasma gasification operations are often proprietary.

15.6 Market Potential of PG Technology

The profitability of any individual facility appears to depend on a number of other factors, including economic considerations, facility costs, feedstock availability, products range, and the permitting process (Artemov et al. 2012). There are several factors that affect the cost and ultimately the profitability of PG waste-to-energy conversion operations, and these are shown in Fig. 15.3.

The sensitivity of the estimated cost and expected revenues from the sale of syngas and heat coproduced by the conversion of waste depends on the world markets and prices for energy and industrial materials. At present, little data is available for currently operating facilities and how these facilities would be affected by market changes. The value of PG process is attributed to the combination of the avoided cost of conventional disposal and the expected revenue stream from coproduction (Popov et al. 2011). Table 15.2 summarizes information for different thermal technologies. Information was collected from (1) refereed technical literature and (2) commercial literature and/or referenced websites (Table 15.3).

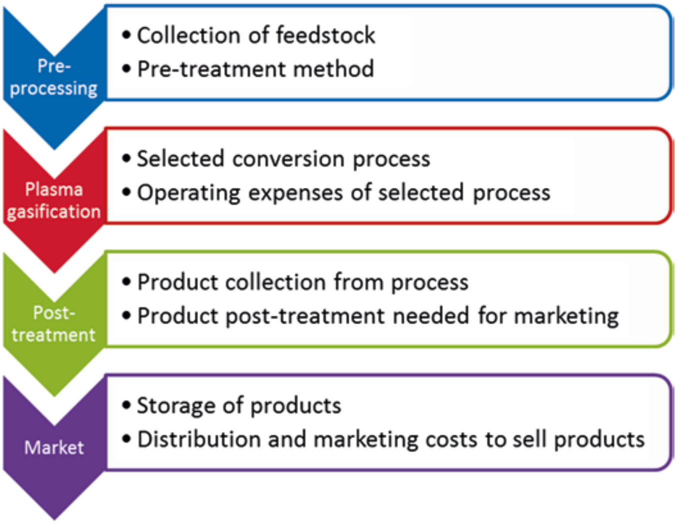

Fig. 15.3 Factors that influence the economic assessment of a plasma gasification facility

Table 15.2 Emissions from thermal plasma treatment facilities (Bowyer and Fernholz)

Emission	Unit	USERPA standard	EC 2000/76 standard	Unit[a]	Unit[b]	Unit[c]
PM	mg/Nm3	20	14	3.3	<3.3	12.8
HCL	mg/Nm3	40.6	14	6.6	2.7	3.1
NOx	mg/Nm3	308	281	74	162	150
SOx	mg/Nm3	85.7	70	–	–	26
Hg	mg/Nm3	50	14	0.0002	0.00067	0.0002
Dioxins/furans	ng/Nm3	13	0.14	0.000013	0.0067	0.009245

[a]EPA Environmental Technology Verification Testing (2000) of InEnTec Plasma Arc Gasification of 10 tpd of Circuit Boards, Richland, Washington
[b]EPA Environmental Technology Verification Testing (2000) of InEnTec Plasma Arc Gasification of 10 tpd of Medical Waste, Richland, Washington
[c]Results of Third-Party Demonstration Source Tests (2008–2009) of Plasco Energy Plasma Arc Gasification of 110 tpd of MSW, Ottawa, Canada

Table 15.3 Characteristics of different thermal technologies

Property	Pyrolysis	Incineration	Conventional gasification	Plasma gasification
Process temperature	500–800 °C	850–1200 °C	400–900 °C	1500–4000 °C
Atmosphere (agent)	Inert/nitrogen	Air	O_2, H_2O	O_2, H_2O Plasma gas: O_2, N_2, Ar
Feedstock	Biomass and MSW Low flexibility	Mixed MSW High flexibility	MSW, RDF, sludge, medical waste Medium flexibility	MSW, RDF, medical and hazardous waste High flexibility
Produced gases	CO, H_2, CH_4, other hydrocarbons, N_2	CO_2, H_2O, O_2, N_2, NOx, SOx, HCl, VOCs	CO, H_2, CO_2,H_2O, CH_4, N_2*	CO, H_2, CO_2, N_2*, CH_4
Solid phase	Ash, coke (biochar)	Ash (approx. 30% of initial volume)	Ash, char	Ash, char, inert slag (12% of initial volume)
Liquid phase	Pyrolysis oil and water	None	None	None
Emissions	N.A.	Far greater than (plasma) gasification	Less than incineration	Less than gasification and incineration

(continued)

Table 15.3 (continued)

Property	Pyrolysis	Incineration	Conventional gasification	Plasma gasification
Gas cleaning	Intermediate cleaning before gas utilization	Intermediate cleaning before gas utilization	Intermediate cleaning before gas utilization	Cleaner gas is produced after the plasma arc
Pollutants	N.A.	PM, NO_X, SO_X, fly ash, ash,	PM, tars, NO_X, SO_X, dioxins, furans, hydrocarbons, CO, char	Low levels of CO, NO_X, tars, other pollutants vitrified in slag
Energy recovery	N.A.	Lower resulting from excess air leading to more waste heat	Higher from less heat loss (not all chars are broken down)	Higher gross energy recovery
Energy use	N.A.	Heat to electricity (steam boiler)	Heat to electricity Syngas for electricity Other commercial uses	Heat to electricity Syngas for electricity Other commercial uses
Input energy requirements	N.A.	None	Autothermal, partial oxidation	Very high (1200–1500 MJ/tonne of waste)
Power to grid (kWh/ton MSW)	N.A.	544	685	816

Basu (2006, 2010), Higman and Van Der Burgt (2008), De Souza-Santos (2008), Annamalai and Puri (2006), Rezaiyan and Cheremisinoff (2005), Luche et al. (2012), Hrabovsky (2009), Kalinenko et al. (1993), Ghofur et al. (2018), Arazo et al. (2017), Huang et al. (2016), Moustakas et al. (2005, 2008), Mountouris et al. (2006, 2008), Achinas and Kapetanios (2012, 2013) and Bratsev et al. (2009)
NA not available

15.7 Barriers

Three cardinal issues must be addressed for any of PG technology to be implemented successfully: legislative/regulatory, involvement of market and agreements, and social aspect. Regulatory facet is the most essential obstacle for this alteration facility. The local authority must also play the dominant role in the management of solid waste, water, and air. The planned facility that comprises premises, classification, water supply, usableness, site design reconsideration, and air emissions must be audited by the local planning agency. It is obligatory for a PG facility to obtain permission hence to start its construction activities.

Safe agreements to obtain a feedstock availability are required for the profitability of PG projects. The amount of feedstock must be more or less stable through the project's life. A thorough estimation of advantageous and disadvantageous consequences concerning ecosystem, society, and profit must be acquired before a facility passes to the stage of building. If markets are not developed for recycled products from the presorting process, revenue that otherwise would have been generated is lost. Furthermore, if no market share exists and clients are not found for the gas products, the facility will be forced to close due to a lack of revenue. The operating costs of these facilities will depend on (1) costs and quantities of labor used, (2) cost and quantities of utilities and expendable supplies needed to operate the facility, and (3) the capital costs for construction of the facility (Clark and Rogoff 2010).

Disadvantages exist for PG plants, especially in relation to feedstock size, electricity requirements, and cost issues (Loghin 2008; Yang et al. 2011). It is important to note that pretreatment is a key issue with respect to thermochemical processing. In some cases, further research in this area will be required in order to make the technology viable for specific wastes. A large portion of electricity generated is necessary for the operation of the plasma torches. This leads to a net reduction in electricity generation from the facility. It can vary significantly and depends largely on the throughput (Yang et al. 2011).

Moreover, the public's negative association with thermal treatment waste facilities is another barrier that needs to be overcome. In addition, smell, noise, and visual aesthetic complaints are fairly common from affected community members after waste management facilities have been installed.

15.8 Conclusion

The utilization of PG technology may be expanded in the future with continuing improvements in the technology. It is important to obtain a better understanding of this technology and its potential impacts on the environment, the economy, and existing markets. Besides, evaluations show that syngas production through PG is advantageous over other thermochemical techniques because PG is energy-efficient and environmentally friendly technology. Moreover, current research activities aim to improve PG control and therefore the performance of the process, which indicates the growing economic potential of plasma gasification in the coming decades over yet established thermochemical techniques.

References

Achinas S, Kapetanios E (2012) Basic design of an integrated plasma gasification combined cycle system for electricity generation from RDF. Int J Eng Res Technol 1(10):1–8

Achinas S, Kapetanios E (2013) Efficiency evaluation of RDF plasma gasification process. Energy Environ Res 3(1):150–157

Advances Plasma Power official web site. http://www.advancedplasmapower.com

Alter NRG, official web site. http://www.alternrg.com

An'Shakov AS, Faleev VA, Danilenko AA, Urbakh EK, Urbakh AE (2007) Investigation of plasma gasification of carbonaceous technogeneous wastes. Thermophys Aeromech 14(4):607–616

Annamalai K, Puri IK (2006) Combustion science and engineering, 1st edn. CRC Press, Boca Raton

Arazo RO, Genuino DAD, de Luna MDG, Capareda SC (2017) Bio-oil production from dry sewage sludge by fast pyrolysis in an electrically-heated fluidized bed reactor. Sustain Environ Res 27(1):7–14
Artemov AV, Bulba VA, Voshchinin SA, Krutyakov YA, Kudrinskii AA, Ostryi II, Pereslavtsev AV (2012) Technical and economic operation parameters of a high-temperature plasma plant for production and consumption waste conversion. Russ J Gen Chem 82(4):808–814
Basu P (2006) Combustion and gasification in fluidized beds, 1st edn. CRC Press, Boca Raton
Basu P (2010) Biomass gasification and pyrolysis: practical design and theory, 1st edn. Academic, Burlington
Bratsev AN, Popov VE, Rutberg AF, Shtengel SV (2006a) A facility for plasma gasification of waste of various types. High Temp 44:823
Bratsev AN, Popov VE, Shtengel SV, Rutberg AF (2006b) Some aspects of development and creation of plasma technology for solid waste gasification. High Temp Mater Processes 10:549–556
Bratsev AN, Kuznetsov VA, Popov VE, Rutberg AF, Ufimtsev AA, Shtengel SV (2009) Experimental development of methods on plasma gasification of coal as the basis for creation of liquid fuel technology. High Temp Mater Processes 13:147–154
C.H.O-Power, official web site. http://www.cho-power.com
Chang JS, Gu BW, Looy PC, Chu FY, Simpson CJ (1996) Thermal plasma pyrolysis of used old tires for production of syngas. J Environ Sci Health A 31(7):1781–1799
Clark BJ, Rogoff MJ (2010) Economic feasibility of a plasma arc gasification plant, city of Marion, Iowa. In: Proceedings of the 18th annual North American waste-to-energy conference, Orland, Florida, USA May 11–13, NAWTEC 18-3502
Dave PN, Joshi AK (2010) Plasma pyrolysis and gasification of plastics waste – a review. J Sci Ind Res 69:177–179
De Souza-Santos ML (2008) Solid fuels combustion and gasification: modeling, simulation, and equipment operations, 2nd edn. CRC Press, Boca Raton
Ducharme C, Themelis N (2010) Analysis of thermal plasma – assisted waste-to energy processes. In: Proceedings of the 18th annual North American waste-to-energy conference, Orland, Florida, USA May 11–13, NAWTEC 18-3582
Europlama, official web site. http://www.europlasma.com
Fauchais P (2007) Technologies plasma: applications au traitement des déchets. Techniques de l'Ingénieur G2055:1–11
Fourcault A, Marias F, Michon U (2010) Modelling of thermal removal of tars in a high temperature stage fed by a plasma torch. Biomass Bioenergy 34:1363–1374
Ghofur A, Soemarno HA, Putra MD (2018) Potential fly ash waste as catalytic converter for reduction of HC and CO emissions. Sustain Environ Res 28(6):357–362
Higman C, Van Der Burgt M (2008) Gasification, 1st edn. Oxford Press, Oxford
Hlína M, Hrabovský M, Kopecký V, Konrád M, Kavka T (2006) Plasma gasification of wood and production of gas with low content of tar. Czechoslov J Phys 56(B):179–1184
Hrabovsky M (2009) Thermal plasma generators with water stabilized arc. Open Plasma Phys J 2:99–104
Hrabovsky M, Konrad M, Kopecky V, Hlina M, Kavka T (2006) Gasification of biomass in water/gas stabilized plasma for syngas production. Czechoslov J Phys 56(B):1199–1206
Huang YF, Chiueh PT, Lo SL (2016) A review on microwave pyrolysis of lignocellulosic biomass. Sustain Environ Res 26(3):103–109
InEnTe, official web site. http://www.inentec.com
Kalinenko RA, Kuznetsov AP, Levitsky AA, Messerle VE, Mirokhin YA, Polak LS, Sakipov ZB, Ustimenko AB (1993) Pulverized coal plasma gasification. Plasma Chem Plasma Process 13(1):141–167
Leal-Quirós E (2004) Plasma processing of municipal solid waste. Braz J Phys 34:1587–1593
Loghin I (2008) Market barriers to the integrated plasma gasification combined cycle plant implementation – Romanian case. UPB Sci Bull Ser C 70(2):111–120

Luche J, Falcoz Q, Bastien T, Leninger JP, Arabi K, Aubry O, Khacef A, Cormier JM, Lédé J (2012) Plasma treatments and biomass gasification. IOP Conf Ser Mater Sci Eng 29:012011
Mountouris A, Voutsas E, Tassios D (2006) Solid waste plasma gasification: equilibrium model development and exergy analysis. Energy Convers Manag 47:1723
Mountouris A, Voutsas E, Tassios D (2008) Plasma gasification of sewage sludge: process development and energy optimization. Energy Convers Manag 49(8):2264
Moustakas K, Fatta D, Malamis S, Haralambous K, Loizidou M (2005) Demonstration plasma gasification/vitrification system for effective hazardous waste treatment. J Hazard Mater B 123:120–126
Moustakas K, Xydis G, Malamis S, Haralambous KJ, Loizidou M (2008) Analysis of results from the operation of a pilot plasma gasification/vitrification unit for optimizing its performance. J Hazard Mater 151:473–480
Murphy AB, Farmer AJD, Horrigan EC, McAllister T (2002) Plasma destruction of ozone depleting substances. Plasma Chem Plasma Process 22(3):371–385
Nema SK, Ganeshprasad KS (2002) Plasma pyrolysis of medical waste. Curr Sci 83(3):271–278
PEAT International, official web site. http://www.peat.com
Plasco Energy Group, official web site. http://www.plascoenergygroup.com
Plasma Arc Technologies, official web site. http://www.plasmaarctech.com
Popov VE, Bratsev AN, Kuznetsov VA, Shtengel SV, Ufimtsev AA (2011) Plasma gasification of waste as a method of energy saving. J Phys Conf Ser 275:012015
Pyrogenesis Canada, official web site. http://www.pyrogenesis.com
Rezaiyan J, Cheremisinoff NP (2005) Gasification technologies: a primer for engineers and scientists, 1st edn. CRC Press, Boca Raton
Serbin SI, Matveev IB (2010) Theoretical investigations of the working processes in a plasma coal gasification system. IEEE Trans Plasma Sci 38(12):3300–3305
Tendler M, Rutberg P, Van Oost G (2005) Plasma based waste treatment and energy production. Plasma Phys Control Fusion 47:A219–A230
Tetronics International, official web site. http://www.tetronics.com
Vaish B, Srivastava V, Singh P, Singh A, Singh PK, Singh RP (2016) Exploring untapped energy potential of urban solid waste. Energy Ecol Environ 1(5):323–342
Vaish B, Sharma B, Srivastava V, Singh P, Ibrahim MH, Singh RP (2019) Energy recovery potential and environmental impact of gasification for municipal solid waste. Biofuels 10:87–100
Westinghouse Plasma, official web site. http://www.westinghouse-plasma.com
Yang L, Wang H, Wang H, Wang D, Wang Y (2011) Solid waste plasma disposal plant. J Electrost 69:411–413