ENC-2020-0657
TECHNICAL STUDIES OF BIOMEDICAL WASTE PLASMA GASIFICATION

[1]Regina Franciélle Silva Paulino, regina.paulino@unesp.br
[1]Omar R. Llerena-Pizarro, omar.llerena@unesp.br
[1]Luciana Sales Leite Galvão Araujo, luciana.sales@unesp.br
[2]Alexei Mikhailovich Essiptchouk, alexei.essiptchouk@unesp.br
[1]José Luz Silveira, jose.luz@unesp.br

[1]Laboratory of Optimization of Energy Systems (LOSE), Department of Energy, School of Engineering, and Institute of Bioenergy Research (IPBEN-UNESP)-Associated Laboratory of Guaratinguetá, Sao Paulo State University (UNESP), SP, Brazil.
www.feg.unesp.br/ipben
[2]Department of Environmental Engineering, Institute of Science and Technology, São José dos Campos, Sao Paulo State University (UNESP), SP, Brazil

Abstract. *Brazil has problems with biomedical waste (BW) incorrect disposal. New technologies studies to mitigate that problem are becoming increasingly important. The plasma gasification technology can destroy a range of materials, producing, as a result, an inert slag and syngas. The slag can be used in civil construction, whereas syngas can be burned in an internal combustion engine (ICE) for electricity and heat production. This paper aims to carry technical studies of plasma gasification of 3000 t/month of BW to determine the amount of syngas and slag produced and figure out the potential for electricity production by burning the produced syngas in the internal combustion engine.*

Keywords: plasma gasification, biomedical waste, syngas, electricity.

1. INTRODUCTION

Brazil is not an example when it comes to the proper disposal of biomedical waste (BW). The Report on the Diagnosis of Solid Waste from Health Services, carried out by IPEA (2012), pointed out that 41.5% of Brazilian municipalities do not perform any type of BW treatment.

Inadequate biomedical waste management causes major environmental problems, can contaminate and elevate hospital infection rates, generate epidemics and pollute groundwater. Thus, it is essential that Brazilian municipalities mobilize to insert technologies that aim at the correct disposal of BW [CAFURE and PATRIARCHA-GRACIOLI, 2015].

The heat treatment and gasification are one of the most effective hazardous waste disposal technologies. However, there are many substances when treated with conventional processes are not neutralized and can cause prejudices to the environment and human health. The plasma technology is designed to alleviate or eliminate this problem by destroying all wastes containing harmful substances [ZHOVTYANSKY and VALINCIUS, 2018].

The waste plasma gasification exploits the thermochemical properties. The plasma provides the energy necessary to maintain the temperature inside the reactor at enough values for the gas molecules dissociation produced by material decomposition. Due to the high temperature, inorganic components are melted, organic components are volatilized and complex molecules are dissociated. The organic materials, containing mainly chemically bonded carbon, hydrogen, and oxygen, are broken down into syngas which can be used as a high-quality fuel or in the chemical synthesis industry [HRABOVSKY and VAN DER WALT, 2019].

The plasma gasification technology is recommended for processing municipal, commercial, industrial, petrochemical, and biomedical waste. The clean syngas produced by plasma gasification can be converted into a wide product variety, including electricity, through gas turbines, alternative engines, and, in the future, fuel cells, heat, and steam [ZHOVTYANSKY and VALINCIUS, 2018].

The plasma gasification has also gained interest in the production of syngas and electricity generation in recent years, as costs have entered a commercially competitive range. A plasma gasification plant in Utashinai, Japan, has been in operation since 2002 and, as of 2014, it gasifies 268 tonnes of municipal solid waste per day and, producing 7.9 MWh of electricity [Sikarwar et. al, 2016].

New technologies must be implemented to eliminate biomedical waste and produce energy. The plasma gasifiers installed worldwide are of high capacity and the vast majority are used to process a few cases BW. Considering the incorrect disposal of BW in Brazil, this paper aims to present a technical methodology applied to biomedical waste plasma

gasification. Technical studies are carried out to determine the production and electricity generation capacity from gas flaring or the plasma gasification feature in the internal combustion engine.

2. MATERIALS AND METHODS
2.1 MATERIALS

In Brazil, there is little research on biomedical waste characterization, making it difficult to develop new research. For this paper, consider a biomass characterization study carried out in a hospital in the São Carlos city, São Paulo, Brazil, where it was only possible to evaluate the occurrence percentage, since the only visual characterization of the residues is allowed, harming the indication by weight and specific mass of each component. Thus, the materials with the highest occurrence are shown in Table 1.

Table 1. Materials with the highest occurrence in the BW in Brazil [GIL, 2020]

Element	[%]
Paper	76.2
Plastic	57.0
Surgical gloves	43.9
Disposable cups	39.9
Paper used in the bathroom	28.7
Leftover food or easily degradable material	23.8

The composition chemical of BW used for technical analysis of the plasma gasification process, are shown in Table 2 [GIL, 2020].

Table 2. Biomedical waste composition in Brazil [GIL, 2020]

Substance	%
C	35.73
H	3.87
O	37.40
N	0.51
S	0.00
Cl	0.32
Moisture	18.33

In the plasma gasification process of waste is produced syngas, it goes through a cooling system to reduce the temperature from 1600 °C to 800 °C, the temperature indicated to enter the ICE, and then it is taken to the cleaning system to remove all impurities. Finally, the syngas is burned in the internal combustion engine to generate electricity. The process diagram is shown in Fig. 1
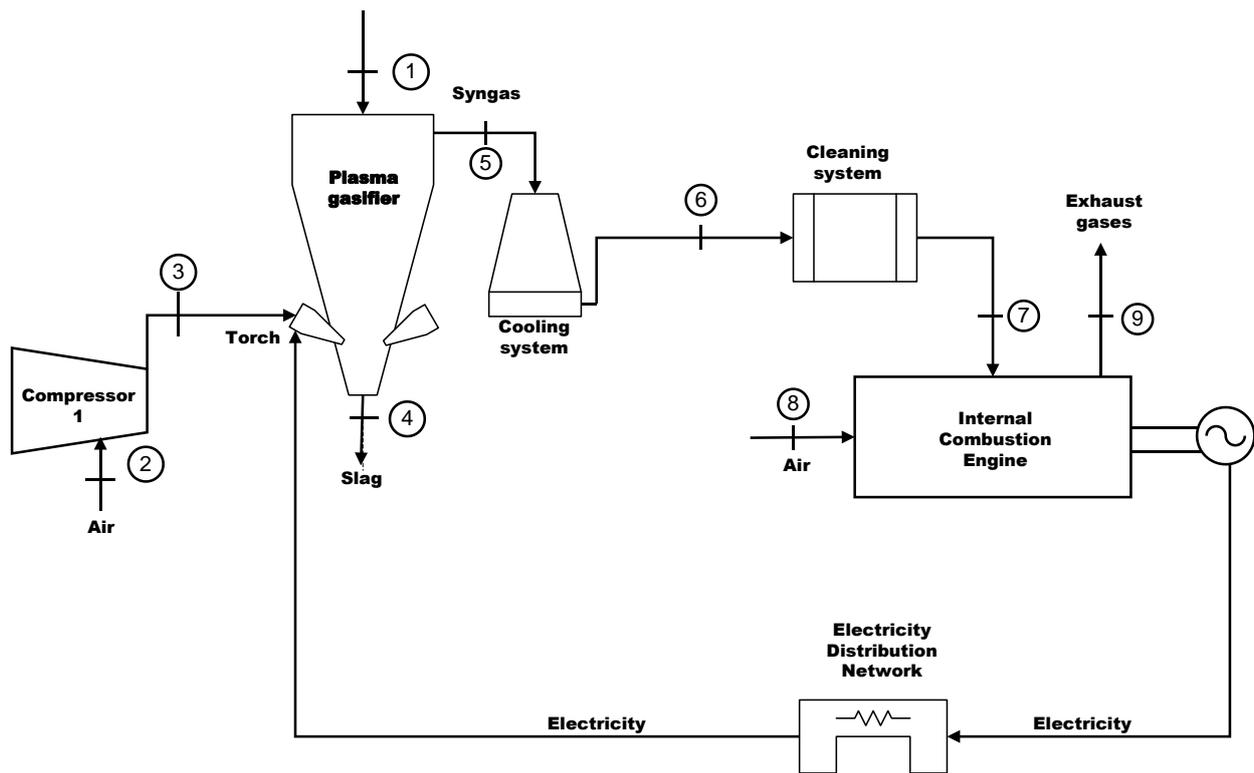
Figure 1: Plasma gasification process associated ICE scheme.

2.2 TECHNICAL ANALYSIS

The technical analysis of the plasma gasifier aims to determine the waste and air mass flow, beyond slag and syngas through mass conservation, being it is also determined its energetic efficiency.

The plasma gasifier has a biomedical waste inlet (point 1), air inlet (point 3), slag outlet (point 4), and syngas outlet (point 5). Eq. (1) presents the mass conservation applied to this control volume.

$$\dot{m}_1 + \dot{m}_3 = \dot{m}_4 + \dot{m}_5 \tag{1}$$

Through the product between air volume, air factor, specific mass, and waste mass flow is determined the air mass flow. The air volume (AV) can be calculated by Eq. (2) [PÉREZ et. al, 2014].

$$AV = \left(0.0889.\left(C_C + (0.375.C_S)\right)\right) + (0.265.C_H) - (0.0333.C_O) \tag{2}$$

The air factor is determined by Eq. (3).

$$\text{AF (T)}= -058+(1,17.10^{-3}.\text{T})-(2,93.10^{-7}.\text{T}^2)+(6,89.10^{-11}\text{T}^3) \tag{3}$$

The Eq. (4) determinates the air mass flow.

$$\dot{m}_3 = AV * AF * \rho_{air} * \dot{m}_1 \tag{4}$$

Where:
AF: air factor [-]
AV: air volume [Nm^3/kg]
$\dot{m}_1$: waste mass flow (point 1) [kg/s]
$\dot{m}_3$: air mass flow (point 3) [kg/s]
$\dot{m}_4$: slag mass flow (point 3) [kg/s]
$\dot{m}_5$: syngas mass flow (point 4) [kg/s]
ρ_{air}: air specific mass [kg/m^3]

The syngas mass flow is determined by the Eq. (5) [MESSERLE et. al, 2018].

$$\dot{m}_5 = 1,68.\dot{m}_1 \tag{5}$$

The syngas lower heating value is determined by the equation Eq. (6) [VICENTINI, 2011].

$$LHV_{syngas} : \frac{-(H_P - H_R)}{MM_c} \tag{6}$$

Where:
LHV_{syngas}: syngas lower heating value [kJ/kg]
H_p: Product enthalpy [kJ/kmol]
H_R: Reagent enthalpy [kJ/kmol]
MM_c: Molar mass of syngas [kmol/kg]

Table 3 presents the syngas composition of MSW and BW plasma gasification.

Table 3. Syngas composition of BW [MESSERLE et. al, 2018]

Substance	BW[%]
H_2	44,6
CO	26,5
N_2	29,9

The Eq. (7) shows the combustion reaction of syngas from BW with excess air of 40% [FILHO et. al, 2013].

$$0,446H_2 + 0,265CO + 0,299N_2 + 0,36O_2 + 1,34N_2 \rightarrow 0,27CO_2 + 0,45H_2O + 2,16N_2 + 0,14O_2 \tag{7}$$
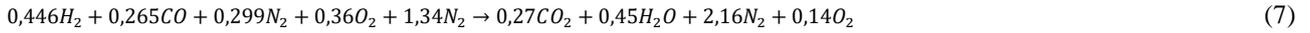
Table 4 shows the enthalpy difference, formation enthalpy, and molar mass of the syngas composition elements.

Table 4. Enthalpy difference, formation enthalpy, and molar mass [BORGNAKKE and SONNATAG, 2013]

Substance	$\Delta\bar{h}$[kJ/kmol]$_{973\,K}$	$\bar{h}_f^0$[kJ/kmol]$_{298\,K}$	MM [kmol/kg]
CO_2	31947,9	-393522	44
CO	20797,9	-110527	28
H_2	20632,9	0	2
N_2	20588,2	0	28
CH_4	35964	-74873	16
O_2	21768,26	0	32
H_2O	24902,9	-241826	18

The enthalpy of products from Eq. (6) is calculated using Eq. (8) for BW.

$$H_{P.BW} = 0.27(\Delta\bar{h} + \bar{h}_f^0)_{CO_2} + 0.45\,(\Delta\bar{h} + \bar{h}_f^0)_{H_2O} + 2.16\,(\Delta\bar{h} + \bar{h}_f^0)_{O_2} + 0.14\,(\Delta\bar{h} + \bar{h}_f^0)_{N_2} \tag{8}$$

The enthalpy of reagents from Eq. (6) can be determined using (9) for BW.

$$H_{R.BW} = 0.27(\Delta\bar{h} + \bar{h}_f^0)_{CO} + 0.45\,(\Delta\bar{h} + \bar{h}_f^0)_{H_2} + 0.29\,(\Delta\bar{h} + \bar{h}_f^0)_{N_2} + 0.36\,(\Delta\bar{h} + \bar{h}_f^0)_{O_2} + 1.33\,(\Delta\bar{h} + \bar{h}_f^0)_{N_2} \tag{9}$$

The Eq. (10) determines the syngas molar mass from BW.

$$MM_{c.BW} = 0.265MM_{CO} + 0.446MM_{H_2} + 0.299MM_{N_2} \tag{10}$$

The BW lower heating value can be calculated using Eq. (11) [VICENTINI, 2011].

$$PCI_R = 38834C_C + 93868C_H + 101325C_S - 5945C_N - 10802C_O - 2449C_{H_2O} \tag{11}$$

The author Messerle et. al (2018), concluded in their work that specific energy input to the plasma reactor BW gasification process, as estimated in the experiments, ranged from 2.88 to 4.5 kWh/kg. For these studies is used the value of 3.38 kWh/kg$_{BW}$

The energy required by the torch is obtained through Eq. (12):

$$\dot{E}_{torch} = \frac{\dot{m}_1 . \dot{e}_{req.gp} . 3600}{\eta_{torch}} \tag{12}$$

Where:
$e_{req.gp}$.: specific energy required in the plasma gasification process [kWh/kg]
$\dot{E}_{torch}$: plasma torch power [kW]
$\dot{m}_1$: waste mass flow (point 1) [kg/s]
η_{torch}: torch efficiency [-]

The plasma gasifier energetic efficiency is the ratio between syngas energetic and energy supplied by the waste plus the electrical energy required in the torch. The Eq. (13) is used to calculate plasma gasifier energetic efficiency.

$$\eta_{pg} = \frac{\dot{m}_4 . LHV_{syngas}}{\dot{m}_1 . LHV_W + \dot{E}_{torch}} \tag{13}$$

Where:
$\dot{E}_{torch}$: plasma torch power [kW]
LHV_w: waste lower heating value [kJ/kg]
LHV_{syngas}: syngas lower heating value [kJ/kg]
$\dot{m}_1$: waste mass flow (point 1) [kg/s]
$\dot{m}_4$: syngas mass flow (point 4) [kg/s]
η_{pg}: plasma gasifier energy efficiency [-]

Typically, internal combustion engines that use natural gas and biogas ICE at the same time are currently under development. However, when these engines use another type of biofuel, such as syngas, which has less low heating value (LHV), the ICE final performance is reduced, mainly concerning electricity production and electricity generation efficiency [WANG et. al, 2015].

To select the best ICE was considered the electricity generation efficiency, which is determined by Eq. (14). Through this selection, it is possible to determine the electricity generation potential in ICE from the syngas produced amount in the plasma gasification process, and thus select the best commercially available ICE:

$$\eta_{el.ICE} = \frac{\dot{E}_{p.ICE}}{\dot{E}_{syngas}} \tag{14}$$

Where:

$\dot{E}_{p.ICE}$: ICE electrical power [kW]
$\dot{E}_{syngas}$: energy supplied by syngas [kW]
$\eta_{el.ICE}$: ICE electricity generation efficiency [kW]

The electricity generation efficiency of syngas ICE is 14-26% [MAYA et. al, 2016]. In this work is used the value of 20%. The syngas energy supplied is determined by Eq. (15):

$$\dot{E}_{syngas} = \dot{m}_{syngas} . LHV_{syngas} \tag{15}$$

Where:

$\dot{E}_{syngas}$: energy supplied for syngas [kW]
LHV_{syngas}: syngas lower heating value [kJ/kg]
$\dot{m}_{syngas}$: syngas mass flow [kg/s]

When a fuel other than natural gas is used in ICE, with lower LHV, Wang, et. al (2015) proposes Eq. (16) to determine electricity generation efficiency.

$$\eta_{el.ICE} = \frac{\dot{E}_{p.ICE}}{\dot{E}_{syngas} \cdot \gamma_{LHV}}$$ (16)

Where:
$\dot{E}_{p.ICE}$: ICE electrical power [kW]
$\dot{E}_{syngas}$: energy supplied for syngas [kW]
γ_{LHV}: LHV correction factor [-]
$\eta_{el.ICE}$: ICE electricity generation efficiency [kW]

The correction factor for the lower heat value is determined using the Eq. (17):

$$\gamma_{LHV} = 0,102.\frac{LHV_{syngas}}{LHV_{NG}} + 0,897$$ (17)

Where:
γ_{LHV}: LHV correction factor [-]
LHV_{NG}: natural gas lower heating value [kJ/kg]
LHV_{syngas}: syngas lower heating value [kJ/kg]

3. RESULTS AND DISCUSSIONS

Through the technical analysis, it was possible to obtain all mass flows the inlet and outlet of the plasma gasifier, the results are presented in Table 5 for 3000 ton/h of MSW and BW.

Table 5. Inlet and outlet mass flow of gasifier

Mass flow	BW [kg/s]
Waste mass flow (m₁)	1.15
Air mass flow (m₃)	4.88
Slag mass flow (m₄)	4.10
Syngas mass flow (m₅)	1.93

Table 6 presents the electrical power required in plasma torch, the ICE electricity produced with syngas produced in MSW and BW plasma gasification process, the gasifier energetic efficiency using MSW and BW, and the ICE coupled system, and the electricity generation index.

Table 6. Energetic analysis results

Parameters	BW
Syngas lower heating value (LHV_{syngas}) [kJ/kg]	14719
Waste lower heating value (LHV_{waste}) [kJ/kg]	17750
Plasma torch power ($\dot{E}_{torch}$) [kW]	16462
ICE electrical power ($\dot{E}_{p.ICE}$) [kW]	5279
Electricity generation index ($\lambda_{el.MCI}$) [-]	0.32
Plasma gasifier energetic efficiency (η_{pg}) [%]	77.11
Energetic efficiency of the plasma gasification process associated with ICE ($\eta_{gp.el.MCI}$)[%]	15.42

The selected internal combustion engine was two ICE model G 3612 Genset DM5395 with 2615 kW of electrical power for BW.

The syngas produced in BW plasma gasification has a good potential for generating electricity in the internal combustion engine, but the energy consumption is very high for all processing. However, the environmental part must be

taken into account, the destruction of BW in the plasma gasification process is a good option for its disposal, as this type of waste stops polluting the environment, not causing damage to the health of the population and it still generates electricity. Furthermore, the slag can be used to commercialize products in the civil construction area.

Table 7 presents a comparison between the production of electrical power in kW for 3000 t/month of BW of this work and other residues found in the literature, including MSW and BW. Electric power values were found in the literature for other amounts of waste (t/day, t/year, among others), so the values presented in this table were converted to the production of 3000 t/month.

Table 7. Electrical power production

	MSW	BW	RDF [Minutillo]	Wood [Rutberg]	Sewage sludge [Kalinci]	MSW [Ducharme]	MSW [Mountouris]	BW [Paulino]
Electrical power [kW]	3152	5279	4620	5520	1134	2070	4305	5277

4. CONCLUSIONS

The technical analysis applied in this paper made it possible to conclude that the energetic efficiency of the plasma gasifier for BW is 77.11%. And it also made it possible to determine that the potential for electricity production is 5279 kW, but 16462kw of electricity is required for the operation of the plasma gasifier.

Plasma gasification is still a widespread technology, due to its high cost and high electricity consumption as it was produced in the technical analysis. Its feasibility is based on the destruction of BW, which in a large part of Brazil has an incorrect destination, as it is a process that eliminates all waste and still provides the production of energy and products for the civil construction through the slag. This process should be more widespread and applied to all BW production in Brazil, so this technology will develop further, providing technical viability and its cost will become more viable.

Therefore, according to the results, plasma BW gasification, although consuming a lot of energy in the process, still produces surplus energy. In this way, this technology can collaborate for the destruction of BW avoiding soil contamination and pollution of the environment and still generate electricity.

5. ACKNOWLEDGEMENTS

6. REFERENCES

IPEA. Institute of Applied Economic Research. Diagnosis of Solid Waste from Health Services. 2012.

CAFURE, V.A; PATRIARCHA-GRACIOLI, S.R. Les résidus de service de santé et ses impacts environnementaux: une révision bibliographique. INTERAÇÕES, Campo Grande, 2015;16:301-314.

ZHOVTYANSKY V. E VALINCIUS V. Efficiency of Plasma Gasification Technologies for Hazardous Waste Treatment. Gasification for Low-grade Feedstock, 2018, p. 142-189.

HRABOVSKY M. E VAN DER WALT I.J. Plasma Waste Destruction. Springer International Publishing AG 2017 F.A. Kulacki (ed.), Handbook of Thermal Science and Engineering. https://doi.org/10.1007/978-3-319-32003-8_32-1 . [Accessed 02 November 2019].

Sikarwar V. S., Zhao M. , Clough P., Yao J., Zhong X., Mohammad Zaki Memon M. Z., Shah N., Anthony E. J, Fennell P. S. An overview of advances in biomass gasification Energy Environ. Sci., 2016, **9**, 2939-2977.

GIL T. N. L, Qualitative and quantitative characterization of health service waste generated at the Irmandade Santa Casa de Misericórdia de São Carlos, SP. São Carlos School of Engineering, University of Saõ Paulo (USP) 85 p, 2007. (Portuguese).

https:www.tcc.sc.usp.br › disponiveis › publico › Gil_Tatiana_Novis_Lopes

[Accessed 6 February 202].

PÉREZ N. P. , MACHIN, E. B., PEDROSO D. T., ANTUNES J. S., SILVEIRA J. L . Fluid-dynamic assessment of sugarcane bagasse to use as feedstock in bubbling fluidized bed gasifiers. Applied Thermal Engineering, 2014;73:238- 244.

> https://doi.org/10.1016/j.applthermaleng.2014.07.048

MESSERLE V.E., MOSSE A.L, USTIMENKO A.B. Processing of biomedical waste in plasma gasifier. Waste Management .2018;79:791-799.

> https://doi.org/10.1016/j.wasman.2018.08.048

VICENTINI, M. C. Application of Organic Rankine Cycle heat supplied by rice husks and wood waste burning. Graduate Work (Graduate in Mechanical Engineering) – Faculdade de Engenharia do Campus de Guaratinguetá, Universidade Estadual Paulista, Guaratinguetá, 2011 (Portuguese).

FILHO, P. T. D.; SILVEIRA, J. L.; TUNA, C. E.; LAMAS, W. Q. Energetic, ecologic and fluid-dynamic analysis of a fluidized bed gasifier operating with sugar cane bagasse. Applied Thermal Engineering. 2013;57:116-124.

> https://doi.org/10.1016/j.applthermaleng.2013.01.045

BORGNAKKE C., SONNATAG R. E., Fundamentos da Termodinâmica. São Paulo, Blucher, 2013.

WANG, J. ; MAO, T. ; SUI, J. ; JIN, H. "Modeling and performance analysis of CCHP (combined cooling, heating and power) system based on co-firing of natural gas and biomass gasification gas". Energy. 2015;93:801-815.

> https://doi.org/10.1016/j.energy.2015.09.091

MAYA D. M. Y. , SARMIENTO A. L. E., OLIVEIRA C. A. B. DE S., LORA E. E. S., ANDRADE R. V. J. Gasification of Municipal Solid Waste for Power Generation in Brazil, a Review of Available Technologies and Their Environmental Benefits. Chem. Chem. Eng. 2016;10:249-255.

MINUTILLO M., PERNA A., DI BONA D. Modelling and performance analysis of an integrated plasma gasification combined cycle (IPGCC) power plant. Energy Conversion and Management. 2009;50: 2837–2842 . https://doi.org/10.1016/j.enconman.2009.07.002Get

> https://doi.org/10.17265/1934-7375/2016.06.001

RUTBERG PH.G., BRATSEV A.N., KUZNETSOV V.A., POPOV V.E., UFIMTSEV A.A., SHTENGEL S.V. On efficiency of plasma gasification of wood residues. Biomass and Bioenergy. 2011; 35:495-504. https://doi.org/10.1016/j.biombioe.2010.09.010

KALINCI Y., HEPBASLI A., DINCER I. Exergoeconomic analysis of hydrogen production from plasma gasification of sewage sludge using specific exergy cost method. International Journal of Hydrogen Energy. 2011; 36(17):11408-11417. https://doi.org/10.1016/j.ijhydene.2010.11.124

DUCHARME C., THEMELIS N. Analysis of thermal plasma – assisted waste-to energy processes. ASME.Proceedings of the 18th Annual North American Waste-to-Energy Conference, 2010. http://www.seas.columbia.edu/earth/wtert/sofos/nawtec/nawtec18/nawtec18-3582.pdf [Accessed 13 April 2020].

MOUNTOURIS A., VOUTSAS E., TASSIOS D. Plasma gasification of sewage sludge: Process development and energy optimization. Energy Conversion and Management. 2008; 49(8):2264-2271. https://doi.org/10.1016/j.enconman.2008.01.025

PAULINO R. F. S., ESSIPTCHOUK A. M., SILVEIRA J. L. The use of syngas from biomedical waste plasma gasification systems for electricity production in internal combustion: Thermodynamic and economic issues. Energy. 2020; 199: 117419 https://doi.org/10.1016/j.energy.2020.117419

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.