Journal of Cleaner Production 164 (2017) 187–197

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Exergoenvironmental analysis of a waste-based Integrated Combined Cycle (WICC) for heat and power production

Yannay Casas-Ledón [a, b, *], Freddy Spaudo [a], Luis E. Arteaga-Pérez [c, **]

[a] Department of Environmental Engineering, Environmental Science Faculty, EULA-Chile Center, University of Concepción, Chile
[b] Technological Development Unit, University of Concepción, Chile
[c] Chemical Engineering School, Wood Engineering Department, University of Bio-Bío, Chile

ARTICLE INFO

Article history:
Received 27 February 2017
Received in revised form
19 June 2017
Accepted 24 June 2017
Available online 24 June 2017

Keywords:
Municipal solid wastes
Gasification
Exergy efficiency
Life cycle assessment
Exergoenvironmental analysis

ABSTRACT

This paper investigates the exergoenvironmental aspects of a Municipal Solid Wastes (MSW)-fueled Gasification Integrated Combined Cycle (WICC). Accordingly, the environmental impacts associated to exergy destruction, total environmental impact, exergoenvironmental factor and the electricity environmental impacts (EEI) are studied. A sensitivity analysis is carried out in order to have a good insight into WICC plant performance, focusing on MSW environmental impacts (0.1–0.9 millipoints (mPts)/kg MSW) and considering only CO_2 emissions as pollutant formation. The results show that the largest environmental impacts are associated to gasification and are mainly caused by chemical exergy destruction (44%) and pollutants formation (61%). The highest total environmental impact (B_{tot}) corresponds to the highest MSW impact, due to the impacts produced by the changes in the specific exergy of the streams. Discarding CH_4 and CO from pollutants formation, reduced the B_{tot} and EEI by nearly 55%. Furthermore, the calculated EEI values (13.5 mPts/kWh) are lower than that reported for conventional energy systems (i.e. Natural gas: 22–26 mPts/kWh). Therefore, this technology could be a promising alternative for energetic valorization of MSW in the Chilean conditions.

1. Introduction

As consequence of the increment in the global population, the changes in consumption patterns, regional economic development, rapid urbanization and industrialization; the generation of municipal solid wastes have been dramatically increased (Tan et al., 2015). In fact, the Municipal Solid Wastes (MSW) generation rate outstrips the ability of the natural environment to assimilate it. Consequently, finding sustainable solutions for MSW disposal or utilization has become a challenge for municipal authorities.

Approximately 6.5 million tons of MSW per year are currently generated in Chile, resulting in a per capita generation of 1.05 kg/inhabitant per day, with an average organic content of 50% (Ministry of Environment, 2012). As a clear difference with the European Union and United States (EPA, 2016, 2015; Zhao and Richardson, 2003), MSW in Chile are deposited at sanitary landfills (69%), landfills (22%) and garbage dumps (9%), which present significant environmental and legal concerns (Ministry of Environment, 2012). In this sense, more than 50% of municipal wastes has potential to be valued. According to the Chilean Policy for Integrated Management of Solid Wastes (Ministry of Environment, 2012), Waste-to-Energy (WTE) stood out as a promising alternative to overcoming the waste accumulation problems by using them as a non-conventional energy source. In this sense, biochemical and thermochemical pathways are being considered as the main routes for energy valuation of MSW. Specifically, the gasification presents various advantages as compared to traditional energy recovery alternatives (e.g. incineration) (Bellomare and Rokni, 2013; Couto et al., 2015; Luz et al., 2015). The gasification gas is alike a synthesis gas, thus it has similar applications such as chemical synthesis or energy production. Furthermore, when it is integrated to combined heat and power production (CHP), gasification is more efficient than combustion process (Zhang et al., 2012). Several works have been published on the gasification processes, suggesting that the integration of biomass/wastes gasification with combined cycle power plants, constitutes an efficient, safe, clean and cost-effective method for power generation (Boyaghchi and Chavoshi, 2017; Tan et al., 2015).

---

* Corresponding author. Department of Environmental Engineering, Environmental Science Faculty, EULA-Chile Center, University of Concepción, Chile.
** Corresponding author.
E-mail addresses: ycasas@udec.cl (Y. Casas-Ledón), larteaga@ubiobio.cl (L.E. Arteaga-Pérez).

http://dx.doi.org/10.1016/j.jclepro.2017.06.211
0959-6526/© 2017 Published by Elsevier Ltd.

Nomenclature

A	Heat transfer area (m^2)
B	Environmental impact rate of each stream (mPts/h)
b	Environmental impact per exergy unit (mPts/MJ)
B_D	Exergy destruction environmental impact rate (mPts/h)
B_{tot}	Total environmental impact rate of plant (mPts/h)
B_{PF}	Environmental impact rate of pollutants formation (mPts/h)
DH	District heating
$e^o i$	Standard chemical exergy of i elements (kJ/kmol)
ex	Exergy of the material streams (kJ/kmol)
E	Total exergy of each stream (kJ/kmol)
E_D	Exergy destruction (kW)
EEI	Electricity exergoenvironmental impact (mPts/kWh)
$f_{b,k}$	Exergoenvironmental factor of component k (%)
H_0	Specific enthalpy at reference state (kJ/kmol)
H_i	Specific enthalpy at initial state (kJ/kmol)
HHV	Higher heating value (MJ/kg)
LHV	Lower heating value (MJ/kg)
n	Equipment life time (years)
N	Annual operation hours (h)
$Net\text{-}W$	Surplus of Gas turbine power (kW)
$r_{b,k}$	Relative environmental impact difference (%)
S_o	Specific enthalpy at reference state (kJ/kmol)
S_i	Specific entropy at initial state (kJ/kmol)
T_o	Temperature of reference state (K)
P_0	Pressure at reference state (atm)
$W_{A\text{-}comp}$	Air compressor power (kW)
$W_{G\text{-}comp}$	Syngas compressor power (kW)
W_{GT}	Gas turbine power (kW)
W_{pump}	Pump power (kW)
W_{ST}	Steam turbine power (kW)
Y_k	Environmental impact rate of each component k (mPts/h)

Greeks letters

η_{exergy}	Exergy efficiency
η_{pump}	Pump efficiency
β	Exergy-energy ratio

Abbreviations and subscripts

ch	Chemical
comp	Compressor
D	Destruction
f	Fuel
GT	Gas turbine
HEX	Heat exchanger
HRSG	Heat recovery steam generation
in	Inlet streams
k	*kth* component of system
MSW	Municipal solid waste
mPts	Millipoints
0	Reference state
OM	Operating and maintenance
out	Outlet streams
p	Product
ph	Physical
pump	Pump
ST	Steam turbine
S	Gases and solids streams in flow diagram
W	Water streams in flow diagram
WICC	Waste-based integrated combined cycle.

In this sense, Rokni (2015) optimized a MSW gasification plant integrated with a solid oxide fuel cell (SOFC) and a Stirling hybrid system. They reported that these systems were up to 50% more energetically efficient than traditional incineration. Economics of MSW gasification also validates its competitiveness as was addressed by Rentizelas et al. (2014) who determined optimal financial indicators for tri-generation using MSW/biomass blends. Similarly, Luz et al. (2015) addressed economic issues associated to MSW gasification and encountered an important scale-sensitive effect. In a previous paper, Casas Ledón et al. (2016) demonstrated that the integration of MSW gasification with a combined cycle allows producing electricity at a competitive cost (0.07–0.13 US$/kWh) –based on the Chilean market– and with about 54% exergy efficiency. Most of these academic publications, are focused on the techno-economic feasibility of the MSW-based energy systems. However, the economic profit not always implies an environmental benefit. Therefore, comprehensive environmental analysis may be helpful in decision making concerning the implementation of waste-based energy systems.

In this context, the exergoenvironmental analysis is a powerful tool, as it reveals the environmental impact associated with each component within a system and the real sources of this impact, by combining exergy analysis (Szargut et al., 1988; Tsatsaronis, 2011) with life cycle assessment methodology (LCA) (ISO 14040, 2006). The key point, in an exergoenvironmental analysis, is the identification of the location, magnitude and causes of environmental impacts due to thermodynamic inefficiencies within the system components (Meyer et al., 2009b). This is a relatively new method but it has been widely used to evaluate the environmental impacts of several energy conversion systems, such as: conventional and advanced district heating systems (Keçebaş, 2016; Khoshgoftar Manesh et al., 2014; Yürüsoy and Keçebas, 2017), hydrogen production (Boyano et al., 2011; Ozbilen et al., 2016), the reverse osmosis seawater desalination (Blanco-Marigorta et al., 2014), solar-geothermal driven combined cooling, heating and power (CCHP) cycle (Boyaghchi and Chavoshi, 2017), hybrid electrical vehicle thermal direction system (Hamut et al., 2014), and air conditioning systems using thermal energy storage (Mosaffa and Farshi, 2016).

A pioneering work reporting on the exergoenvironmental evaluation of a biomass gasification-based energy system was presented by Meyer et al. (2009b). In this study, the gasifier, heat exchangers and the solid oxide fuel cell were identified as the system components with the highest potential for improving the overall process efficiency. Similarly, Petrakopoulou et al. (2011a) assessed various combined cycle power plants considering chemical looping combustion for 100% and 85% of CO_2 capture by means of exergoeconomic and exergoenvironmental analyses. They demonstrated that the chemical looping, including the total capture of CO_2, reduced the overall environmental impact of the electricity production by 22%, while electricity costs increased by nearly 24%, due to the CO_2 capture stage. More recently, Restrepo and Bazzo (2016) evaluated global greenhouse gases impact in a power plant modified for burning biomass-coal blends, through exergoenvironmental principles. The results demonstrated that co-firing process feed with coal-rice straw mix (12.3 kg $CO_{2\text{-}eq}$/s) is environmental more friendly than pulverized coal (16.43 kg $CO_{2\text{-}eq}$/s).