CHEMICAL ENGINEERING TRANSACTIONS
VOL. 80, 2020
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Eliseo Maria Ranzi, Rubens Maciel Filho

ISBN 978-88-95608-78-5; **ISSN** 2283-9216
DOI: 10.3303/CET2080050

Environmental Impact Analysis of Flue Gases Emissions for a 20 kWe Biomass Gasifier

Daniele Sofia[a,*], Nicoletta Lotrecchiano[b], Domenico Cirillo[c], Maurizio La Villetta[c]

[a]Sense Square srl, Piazza Vittorio Emanuele 10, Fisciano (SA), Italy
[b]Università di Salerno, Diparimento di Ingegneria Industriale, Via Giovanni Paolo II, 132, Fisciano (SA), Italy
[c]Costruzioni Motori Diesel CMD S.p.A., Via Pacinotti, 2, San Nicola La Strada (CE), Italy
danielesofia@sensesquare.eu

Due to the potential ability to support local development, create local employment, and contribute to climate change mitigation decentralized bioenergy CHP systems are receiving increasing attention. With bioenergy CHP systems are possible to achieve energy efficiency by converting primary energy to heat and electricity, replacing fossil fuels and reducing carbon dioxide emissions in the atmosphere. In particular, biomass cogeneration is considered a reliable efficient energy production technology and an effective alternative to reduce greenhouse gas emissions due to their low CO_2 emission, using near biomass production sites (e.g., agricultural activities, forestes), avoiding long supply chains. In this paper, a techno-environmental assessment for a biomass powered micro-scale CHP system based on gasifier combined with an internal combustion engine sized for a maximum electrical and thermal output of 20 kW_e and 40 kW_{th}, is analyzed. CO_2 direct emissions and CO_2 equivalent emissions for NO_2, CO, HC were assessed in order to obtain the final environmental impact of the plant. Several cases were considered changing biomass kind and flue gas treatment systems. Results show that biomass kind has not an impact on the toxic gas emissions, while the bioscrubber is the best flue gas treatment technology to reduce concentrations of all pollutants.

1. Introduction

Cogeneration or Combined Heat and Power (CHP) definition is the simultaneous generation of two different forms of useful energy by one single primary energy source. Cogeneration can be a solution for energy saving and environmental preservation, (Dong et al., 2009), due to the application of a heat exchangers kit to absorb and to recover exhaust heat (Houwing et al., 2011). In this sense, cogeneration plants can achieve energy efficiency levels around 90% and could reduce greenhouse gas emissions by up to 250 million tonnes by 2020 (Sofia et al., 2020).
The Energy Efficiency Directive 2017/27/EU requires each EU country to carry out a comprehensive assessment of the efficiency potential for thermal systems, namely heating and cooling. Efficiency improvements can be achieved in a technologically neutral way, particularly by making use of waste heat and cold from waste incineration, power generation and industry, as well as district heat and cold transmission installations with low losses. In this sense, biomass cogeneration is considered an effective alternative to reduce greenhouse gas emissions due to their low CO_2 emission (Sartor et al., 2014). Many kinds of research have been conducted in recent years to improve the economic and environmental efficiency and effectiveness of biomass cogeneration systems (Sartor et al., 2014).
Biomass CHP systems are operated with different kinds of solid, gaseous as well as liquid fuels or residues. There are various processes for the production of power and heat from biomass, most commonly they are based on either biomass combustion or anaerobic digestion. Solid fuels are wood lignocellulose materials but also other crops, as they are grasses or fruits as well as more or less every other organic residue. Also waste solid material of the lignocellulosic biorefineries is valorized by cogeneration systems, as combustion or gasification of lignin-rich streams (Giuliano et al., 2018a). Under certain circumstances, it may be better to gasify the solid feedstock at first and to use the product gas as a syngas. The syngas is composed of useful gas mix like CO (17-22%vol), H_2 (12-20 %vol) and CH_4 (2-3 %vol) (La Villetta et al., 2017). Such gas can be

Paper Received: 31 October 2019; Revised: 11 March 2020; Accepted: 3 April 2020
Please cite this article as: Sofia D., Lotrecchiano N., Cirillo D., La Villetta M., 2020, Environmental Impact Analysis of Flue Gases Emissions for a 20 Kwe Biomass Gasifier, Chemical Engineering Transactions, 80, 295-300 DOI:10.3303/CET2080050

directly used in gas turbines and internal combustion engines after the cleaning process. In technical literature, in terms of size for bioenergy CHP systems the following classification can be assumed: domestic-scale CHP plants (dCHPs) in the range 0.1 ÷ 5kWe, micro-scale CHP plant (μCHPs) in the range 5 ÷ 50kWe, Small-scale CHP plants (SCHPs) in the range 50 ÷ 1MWe, Medium-scale CHP plants (MCHPs) in the range 1 ÷ 2 MWe and Large-scale CHP plants (LCHPs) > 2MWe (La Villetta et al., 2018). Generally, dCHPs, mCHPs and SCHPs can be used for domestic, local heating and residential buildings, MCHPs and LCHPs can be used for larger buildings, industrial sites or district heating grids. Biomass power plants emissions often represent a limit to the diffusion of these plants due to the lack of social acceptance (Giuliano et al., 2018b). This problem is partially overcome by the small size (less than 200 kWe) and pollution monitoring technologies must be applied in order to model their spread (Sofia et al., 2018). Correct positioning of monitoring points for concentrations of pollutants, in fact, allows the identification of the source of polluting emissions (Sofia et al., 2019). In this work, the environmental assessment of a biomass powered μCHPs based on gasifier combined with an internal combustion engine sized for a maximum electrical and thermal output of 20 kWe and 40 kWth, is carried out. The experimental plan was carried out with the aim to asses environmental aspects of the valorization of four different kinds of biomass, in order to obtain 20 kWe of green power. For each biomass kind, the impact of four different cleaning processes of the flue gases was evaluated.

2. Methods

2.1 MICRO-CHP SYSTEM CMD ECO 20

The CMD ECO 20x is a μCHPs powered with biomass, developed by the Italian company Costruzioni Motori Diesel (CMD) S.p.A.. The considered unit integrates an Imbert downdraft gasifier, syngas cleaning devices, a spark ignition reciprocating ICE and an electrical generator. Waste Heat Recovery (WHR) is realized through the heat exchangers kit in both the engine cooling circuit and the exhaust gas line. The CMD ECO 20x is designed to process woodchips or briquettes of residual materials from wood industry (wood dust, wood furniture factory waste, etc.), agro-industry such as the olive oil industry (exhausted olive pomace mixed with sawdust, olive kernel), rice industry (rice husk), canning industry (chestnut shells and hazelnut shells) and prunings of public green areas, characterized by G30 size (1.50–3.00 cm) with a maximum humidity of 20%.
The μCHPs is able to produce electrical and thermal power up to 20 kWe and 40 kWth, respectively. The system is fully automated, electronically managed at each stage of operation from the automatic loading of biomass/residual material tank into the reactor, to start-up and operation of the reactor, and starting of the generator, up to the realization of the parallel connection with the national electrical grid. Figure 1 shows the CMD ECO 20x system. The woodchips or briquettes of residual materials are moved from the tank to the chamber of the reactor through the conveyor belt and a loading apparatus coupled with an auger placed on the top of the gasifier. The gasification reactions convert the raw materials into syngas. The syngas is sent to a cleaning system characterized by a reactor cyclone, a cooler self-scrubber, a biological filter and a last cyclone. The filtered and cooled syngas is then aspirated by the engine. The ICE through the alternator produces the electrical energy that can be delivered to the national electric grid, while thermal energy can be recovered from ICE exhaust gases, by using the shell and tube heat exchanger, as well as by the engine cooling system using the plate heat exchanger.

Figure 1: μCHPs ECO20x developed by the Italian company Costruzioni Motori Diesel (CMD) S.p.A..

2.2 Gasification of four biomass kinds

Gasification is a thermochemical process run at sub-stoichiometric oxygen ratio able to convert solid fuel, such as biomass, in a gaseous stream that can be used for combined heat and power production, or as intermediate for chemicals production (Giuliano et al., 2019b). A limitation of the technology is represented by the tendency of some types of biomass to create agglomerations of dust (Salehi et al., 2018). The generation of pollutants (e.g. dust, Salehi et al., 2015) is related to the amount of ash present in the biomass fed to the gasifier, but easily eliminated thanks to consolidated technologies also on small sizes. More details about experimental set-up are reported in La Villetta et al. (2018).

The kinds of biomass used to produce electricity in the experimental plan are:

- Commercial wood chips;
- Chips of foliage and dried sprigs of orange;
- Chips of virgin beech bark;
- Chips of poplar by-products.

The difference between these four types of biomass consists of the fact that the standard chips are a commercial product obtained from cutting biomass (e.g., woods), the other three types are residual biomass. In particular, the chips of foliage and dried sprigs of orange are from citrus crops from the Campania region (Italy). The chips of virgin beech bark derived from the regional woods rich of beechs. The chips of poplar by-products derived from the management of regional poplar.

2.3 Flue gas treatment systems

The most polluting compounds contained within the flue gas are CO_2, NOx, CO, and volatile hydrocarbon compounds (HC). In particular, CO_2 is the most important Global Warming Potential gas, in fact, it is possible to refer to equivalent CO_2 emissions all other environmental impacts, particularly those of air pollution (Giuliano et al., 2019a). The nitrogen oxides, NO and NO_2, are two primary and secondary pollutants, respectively. NO can lead to paralysis of the central nervous system. Nitrogen dioxide, derived from NO, is four times more toxic than nitrogen monoxide, it causes irritation to the mucous membranes of the eyes and nose. Carbon monoxide (CO) derived from not total combustion and it combines with hemoglobin to produce carboxyhemoglobin, by binding to the site in hemoglobin that usually carries oxygen. Volatile hydrocarbon compounds (HC) can react with nitrogen oxides or with ozone to produce new oxidation products and secondary aerosols, which can cause sensory irritation symptoms. HC contributes to the formation of tropospheric ozone. For these reasons, the four pollutant compounds have to be removed from the flue gases of the biomass power plant.

The types of flue gas treatment system considered are:

- Without treatment;
- Washing tower;
- Bioscrubber.

In particular, the washing tower consists of a wet scrubber able to remove toxic or smelling compounds from flue gases. In the flue gas scrubber, the gas gets in close contact with fine water drops in a co-current or counter-current flow. This method is more effective when the water drop size gets smaller and the total surface between water or washing fluid and the gas gets larger. The water is recirculated in order to save water and reduce the amount of wastewater.

The bioscrubber consists of a gas scrubber and a biological reactor. In the gas scrubber, to-be-removed components are absorbed from the gas stream by the wash water. In the biological reactor, the pollutants that have been absorbed by the wash water are biologically degraded. The purified scrubbing liquid is circulated to the scrubber, where it is able to reabsorb pollutants.

2.4 Environmental impact analysis

A type of environmental assessment based on the calculation of the equivalent CO_2 (Rodrigues Gurgel da Silva et al., 2019) was carried out. In particular, a 100-years effect was considered to estimate the Global Warming Potential in term of CO_{2eq}. Table 1 reports the equivalent ratio for the four pollutant compounds. The equivalent ratio of CO_2 is equal to 1 kg/kg, the highest one is for HC due to the different height distributions of the ozone changes between the case where CO emissions are increased and the case where HC emissions are increased (Fuglestvedt et al., 1994). Finally, each pollutant concentration (mg/m3) was multiplied by the equivalent ratio in order to identify the global CO_{2eq} emissions for each biomass kind and each flue gas treatment technology.

Table 1: CO_2-equivalent emission parameters

Pollutant	Set-up value
CO (kg_{CO2eq}/kg_{CO}) (Daniel and Solomon, 1998)	224
NOx (kg_{CO2eq}/kg_{NOx}) (Fuglestvedt et al., 1994)	68
HC (kg_{CO2eq}/kg_{HC}) (Fuglestvedt et al., 1994)	403
CO_2 (kg_{CO2eq}/kg_{CO2}) (Fuglestvedt et al., 1994)	1

3. Results

Table 2 shows pollutant concentrations for NOx, CO_2, CO and HC for each biomass kind and each gas treatment technology. From the observation of Table 2, biomass kind has a low effect on the flue gas concentrations, variances are equal to max 1.37 mg^2/m^6 for CO and the bioscrubber process. The lowest variance values are for HC.

Table 2: Pollutants emissions for each biomass kind and each flue gas treatment

NOx mg/m^3	Commercial wood chips	Chips of foliage and dried sprigs of orange	Chips of virgin beech bark	Chips of poplar by-products	Variance (mg^2/m^6)
Without treatment	297.3	296.9	297.0	297.4	0.04
Washing tower	237.9	237.7	236.4	237.9	0.39
Bioscrubber	77.1	77.4	77.3	77.7	0.05
CO_2 mg/m^3	**Commercial wood chips**	**Chips of foliage and dried sprigs of orange**	**Chips of virgin beech bark**	**Chips of poplar by-products**	**Variance (mg^2/m^6)**
Without treatment	394.8	393.1	394.7	394.2	0.47
Washing tower	339.1	337.3	340.1	338.4	1.04
Bioscrubber	136.9	138.7	139.0	138.3	0.63
CO mg/m^3	**Commercial wood chips**	**Chips of foliage and dried sprigs of orange**	**Chips of virgin beech bark**	**Chips of poplar by-products**	**Variance (mg^2/m^6)**
Without treatment	1393.1	1395.6	1394.9	1393.8	0.94
Washing tower	1186.3	1186.0	1187.5	1184.7	1.00
Bioscrubber	517.0	516.5	514.2	517.1	1.37
HC mg/m^3	**Commercial wood chips**	**Chips of foliage and dried sprigs of orange**	**Chips of virgin beech bark**	**Chips of poplar by-products**	**Variance (mg^2/m^6)**
Without treatment	15.4	15.4	15.4	15.4	0.00
Washing tower	12.4	12.3	12.3	12.4	0.00
Bioscrubber	2.6	2.6	2.6	2.7	0.00

Because of this, Figure 2 shows only the mean values for each compound and each gas treatment process. The highest concentrations are for CO (range 500-1’400 mg/m^3), this highlights inefficient combustion of the syngas in the engine. CO_2 concentrations are about 25 % of CO. NOx concentrations are always very low considering the Italian emission limit of 500 mg/m^3. The same is for HC emissions, always lower than the limit of 30 mg/m^3. From Table 2, the percentage of pollutant reduction based on pollutant concentration means changing the flue gas treatment technology. Table 2 shows that the gas treatment process has the same effect on each pollutant. After “without treatment” case, the worst one is always the washing tower, with a high NOx and HC reduction (20 %) and the lowest value of 14 % (for CO_2). The best flue gas treatment technology is the bioscrubber. In this case, a pollutant reduction of 83 % of HC was obtained. The lowest reduction impact of the bioscrubber was for CO compound (63 %), four times lower than the washing tower yet.

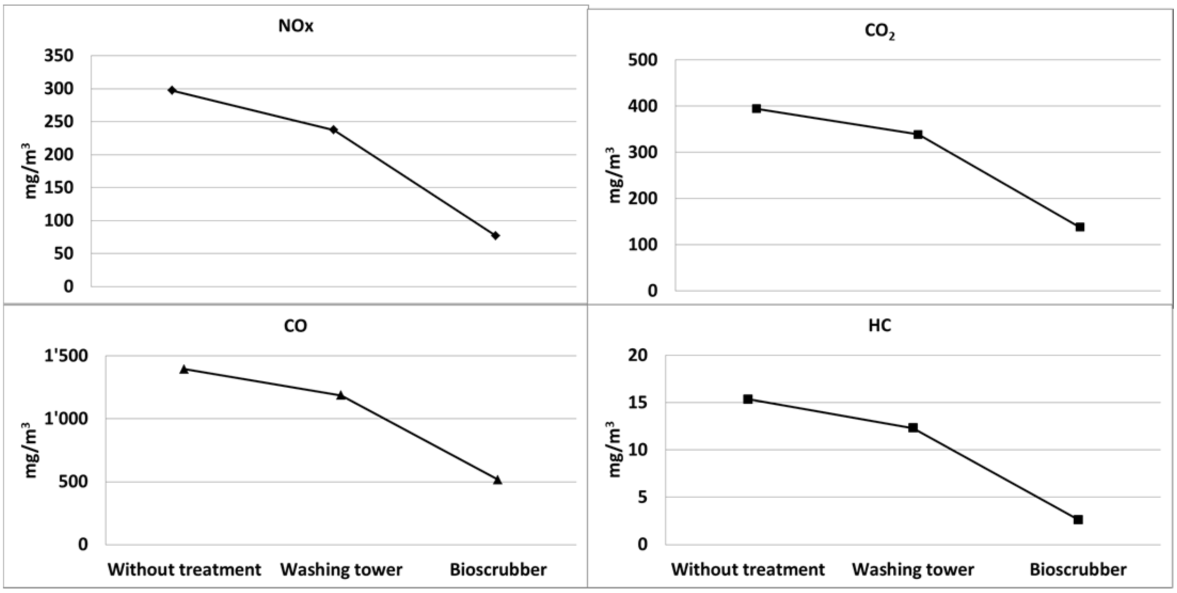

Figure 2: Pollutant concentration means in the flue gases for each gas treatment.

Figure 3 shows the global emission factor in term of gCO_{2eq} for each gas treatment technology. After "without treatment" case, the worst one is the washing tower yet, with 287 gCO_{2eq}/m^3. The best one is bioscrubber. The percentage less for the bioscrubber varies from the range 63-83 of the various compounds to a minus 64%. This because the bioscrubber has the lowest impact on CO, but CO has the highest emissions. The decrease is 15% in the case of the washing tower, this is near previous results for each compound.

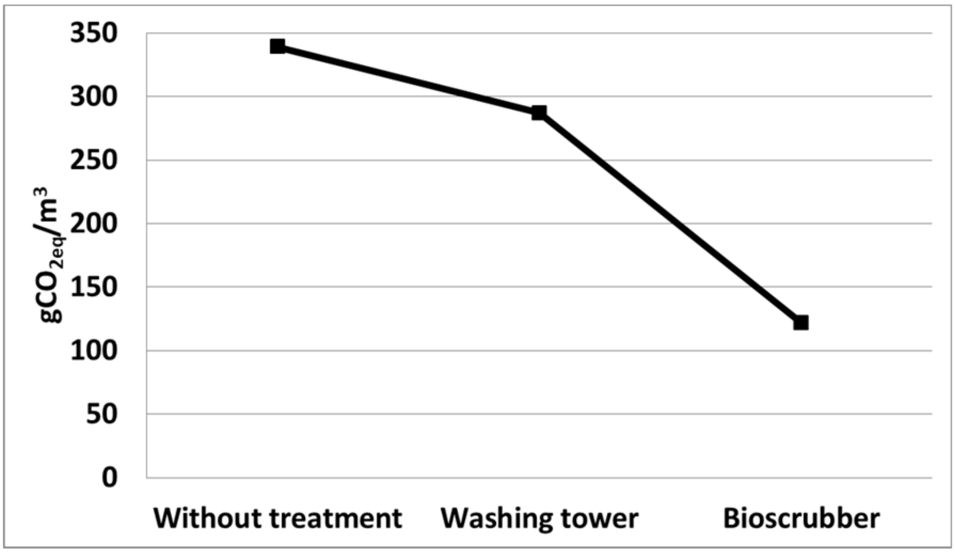

Figure 3: Equivalent CO_2 emissions for four flue gas treatment technology.

4. Conclusions

In this work, an assessment of emissions from a small scale biomass power plant based on the gasification process was carried out. Four different kinds of biomass were tested in the experimental plan. Two different flue gas treatment technologies were compared with pollutant concentrations without treatment: washing tower, bioscrubber. NOx, CO_2, CO, HC, were investigated and their concentrations were transformed to CO_2 equivalent emissions. The bioscrubber process was individuated as the best flue gas treatment technology with a pollutant reduction capacity equal to 63-83 % for single pollutants and equal to 64 % considering the CO_{2eq} emissions.

References

Daniel J.S., Solomon S., 1998. On the climate forcing of carbon monoxide. J. Geophys. Res. Atmos. 103, 13249–13260. https://doi.org/10.1029/98JD00822

Dong L., Liu H., Riffat S., 2009, Development of Small-Scale and Micro-Scale, Biomass-Fuelled CHP Systems: A Literature Review. Applied Thermal Engineering, 29, 2119-2126.

Fuglestvedt J.S. Isaksen I.S.A., Wans W.-C., 1994. Direct and indirect global warming potentials of source gases.

Giuliano A., De Bari I., Motola V., Pierro N., Giocoli A., Barletta D., 2019a. Techno-environmental Assessment of Two Biorefinery Systems to Valorize the Residual Lignocellulosic Biomass of the Basilicata Region. Math. Model. Eng. Probl. 6, 317–323.

Giuliano A., Catizzone E., Barisano D., Nanna F., Villone A., De Bari I., 2019b. Towards Methanol Economy : A Techno-environmental Assessment for a Bio-methanol OFMSW/Biomass/Carbon Capture-based Integrated Plant. Int. J. Heat Technol. 37, 665–674.

Giuliano A., Barletta D., De Bari I., Poletto M., 2018a. Techno-economic assessment of a lignocellulosic biorefinery co-producing ethanol and xylitol or furfural, Computer Aided Chemical Engineering. 2018; 585-590 - doi:dx.doi.org/10.1016/B978-0-444-64235-6.50105-4

Giuliano A., Gioiella F., Sofia D., Lotrecchiano N., 2018b. A Novel Methodology and Technology to Promote the Social Acceptance of Biomass Power Plants Avoiding Nimby Syndrome, CHEMICAL ENGINEERING TRANSACTIONS. vol 67, pp. 307-312 https://doi.org/10.3303/CET1867052

Houwing M., Negenborn R.R., De Schutter B.J., 2011, Demand Response with Micro-CHP Systems. Proceedings of the IEEE, 99, 200-213.

La Villetta M., Costa M., Cirillo D., Massarotti N., Vanoli L., 2018, Performance analysis of a biomass powered micro-cogeneration system based on gasification and syngas conversion in a reciprocating engine, Energy Conversion and Management, 175, 33-48.

La Villetta M, Costa M, Massarotti N., 2017, Modelling approaches to biomass gasification: A review with emphasis on the stoichiometric method. Renew Sustain Energy Rev, 74,71–88.

Rodrigues Gurgel da Silva A., Giuliano A., Errico M., Rong B.-G., Barletta D., 2019. Economic value and environmental impact analysis of lignocellulosic ethanol production: assessment of different pretreatment processes. Clean Technol. Environ. Policy 21, 637–654. https://doi.org/https ://doi.org/10.1007/s1009 8-018-01663 -z

Salehi H., Sofia D., Schütz D., Barletta D., Poletto M., 2018. Experiments and simulation of torque in Anton Paar powder cell. Part. Sci. Technol. 36, 501–512. https://doi.org/10.1080/02726351.2017.1409850

Salehi H., Sofia D., Barletta D., Poletto M., 2015. Dust generation in vibrated cohesive powders. Chem. Eng. Trans. 43, 769–774. https://doi.org/10.3303/CET1543129

Sofia D., Gioiella F., Lotrecchiano N., Giuliano A., 2020. Cost-benefit analysis to support decarbonization scenario for 2030: A case study in Italy. Energy Policy, vol. 137, 111137. https://doi.org/https://doi.org/10.1016/j.enpol.2019.111137

Sofia D., Giuliano A., Gioiella F., 2018. Air Quality Monitoring Network for Tracking Pollutants: the Case Study of Salerno City Center. Chem. Eng. Trans. 68, 67–72. https://doi.org/10.3303/CET1867052

Sofia D., Lotrecchiano N., Giuliano A., Barletta D., Poletto M., 2019. Optimization of number and location of sampling points of an air quality monitoring network in an urban contest. Chem. Eng. Trans. 74, 277–282. https://doi.org/10.3303/CET1974047

Sartor K., Quoilin S. and Dewallef P., 2014, Simulation and Optimization of a CHP Biomass Plant and District Heating Network, Applied Energy, 130, 474-483.