Environmental Engineering and Management Journal

July 2019, Vol. 18, No.7, 1391-1397
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

CARBON FOOTPRINTS ASSOCIATED WITH ELECTRICITY GENERATION FROM BIOMASS SYNGAS AND DIESEL

Filipi Maciel de Melo[1], Alysson Silvestre[1], Monica Carvalho[2*]

[1]Graduate Program in Mechanical Engineering, Federal University of Paraíba, João Pessoa, Brazil
[2]Department of Renewable Energy Engineering, Federal University of Paraíba, João Pessoa, Brazil

Abstract

The limited availability of fossil fuels, as well as the already proven effects of global warming, highlight the need for alternative, environmentally-friendly energy generation. Consideration of primary energy inputs from new and renewable energy resources and technologies represent a major scientific challenge, and a major innovation if realized. This will open up new opportunities for benefit and realized value, in the form of lower costs of energy supply, through the utilization of indigenous energy resources, with reduced carbon emissions. This work applied the Life Cycle Assessment (LCA) methodology to quantify the carbon footprint associated with electricity generation, comparing two different fuels utilized in an experimental generator group. The first fuel was diesel, which was fed to an internal combustion engine attached to a synchronous generator. The second fuel was biomass (woody residues), which was gasified and then utilized in the same combustion engine (after *ottolization* conversion). The functional unit considered herein was the production of 100 kWh of electricity. Diesel fuel presented unsatisfactory results, emitting higher levels of greenhouse gases (1.092 kg CO_2-eq/kWh). Woody biomass helped produce electricity more sustainably (0.269 kg CO_2-eq/kWh), evidencing a possibility of mitigating climate change, with overall avoided emissions of 0.823 kg CO_2-eq/kWh with fuel substitution.

Key words: biomass, carbon footprint, diesel, electricity, life cycle assessment

Received: May, 2017; Revised final: January, 2017; Accepted: March, 2018; Published in final edited form: July 2019

1. Introduction

The current world energy scenario still indicates a high dependence on fossil fuels; according to the International Energy Agency (IEA), in 2017 fossil fuels (e.g., mineral coal, petroleum, and natural gas) represented 80.9% of the world's primary energy offer (IEA, 2017).

The diesel engine is part of modern society, powering transportation, generating electricity, and is utilized in several farming, construction, and industrial activities. However, diesel fuel utilization is associated with several forms of pollution, and environmental concerns now include human health and well-being, as well as damage to ecosystems (Lloyd and Cackette, 2001; Novelli et al., 2017). The environmental impacts associated with diesel fuel atmospheric emissions are mainly related to the sulfur and polycyclic aromatic hydrocarbons. Incomplete burning also emits pollutants such as particulate material, carbon monoxide, and non-burned fractions of hydrocarbons (Nel, 2005). Brazilian diesel is still a very pollutant fuel and presents low quality when compared to international standards, due to its high sulfur content (Botelho, 2012). In the international and Brazilian markets, biomass has been considered as one of the main alternatives to diversify the energy matrix and decrease the use of fossil fuels. In Brazil, the availability of biomass is mainly associated with wood industry residues and the sugar and alcohol sector;

* Author to whom all correspondence should be addressed: e-mail: monica@cear.ufpb.br; Phone: +55 (83) 3216 7268

woody residues and sugarcane bagasse present the greatest potential for use in the short and medium terms, but other residues (rice straw and husk, wood bark) can also represent other promising sources of biomass (Delgado et al., 2018).

The most important use for locally-available biomass can be its use in modern combustion technologies. Gasification is a thermal conversion process that produces a gaseous fuel referred to as synthesis gas (or syngas). Biomass-originated syngas (from now on referred to as biomass syngas) can be used in steam generators, ceramic dryers, and in internal (Diesel and Otto) and external (Stirling) combustion engines, gas turbines, and even fuel cells.

The limited availability of fossil fuels, as well as the already proven effects of global warming, highlight the need for alternative, environmentally-friendly energy. The potential contribution of biomass to the sustainable energy development was discussed by Demirbas et al. (2009) and was considered to present the highest potential to contribute to the energy needs of modern society.

There is scientific consensus that Life Cycle Assessment (LCA) is one of the best methodologies for the evaluation of the environmental burdens associated with different activities, by identifying energy and materials utilized and also the waste and emissions produced, enabling the identification of opportunities for environmental improvement (Cherubini et al., 2009). Already in 2001, the environmental impacts of electricity generation systems were quantified by LCA, highlighting the growing environmental concerns associated with meeting the energy demands of modern society (Gagnon et al., 2002). Recent trends in the study of energy supply systems include environmental aspects (Bravo et al., 2012, 2014; Carvalho et al., 2011, 2012a, 2012b; Carvalho and Delgado, 2017; Lozano et al., 2014; Silva et al., 2017) even including biomass as an energy utility (Araújo et al., 2018; Carvalho et al., 2017; Carvalho and Millar, 2012; Delgado et al., 2016; Delgado et al., 2018).

The objective of this manuscript was to quantify and compare the carbon footprints associated with electricity production, in an experimental generator driven by diesel and biomass syngas, and verify the potential for climate change mitigation in fuel substitution.

2. Materials and methods

2.1. Life Cycle Assessment

LCA studies have been expanding and extending, especially after standardization by International Organization for Standardization (ISO 14040, 2006; ISO 14044, 2006). In Brazil, international standards have been translated and published by the BATS (2014a; 2014b). In Brazil, the first LCA studies were carried out in the 2000s, and nowadays, there are several initiatives to disseminate life cycle thinking (Willers and Rodrigues, 2014).

LCA is an internationally validated and consolidated methodology to assess material and energy flows and consequential environmental impacts of a system throughout its life cycle. The term "life cycle" includes the extraction of raw materials, manufacture, packaging, transportation, utilization, maintenance, and final disposal (Guinée, 2001; 2002). LCA can be applied to products, processes, activities, and even services.

The LCA process is a systematic approach composed by four components: definition of goals and scope; inventory construction; impact analysis; and interpretation of results (Guinée, 2001, 2002; ISO 14040, 2006; ISO 14044, 2006). Goal and scope definition defines and describes the product, process or activity, establishing the context of the evaluation and identifying the limits and environmental effects to be included in the assessment. The construction of the inventory identifies and quantifies the use of energy, water and materials, and the environmental discharges (e.g., air emissions, deposition of solid residues, discharges of liquid effluents) associated with the functional unit of the study (to which all inputs and outputs relate to). Impact analysis required the selection of an impact assessment method, which analyzes the effects of the utilization of energy, water, materials, and the environmental discharges identified in the inventory. The interpretation step evaluates the results from the inventory analysis and application of the environmental impact evaluation method. The conclusions and recommendations for decision-making can be obtained from these results. More details can be found in Guinée (2001, 2002).

2.1.1. Software, database, and method for evaluation of environmental impacts

The software utilized to carry out LCA herein was SimaPro® 8.2.0.0, developed by (PréConsultants, 2015). This software follows the ISO standards (ISO 14040, 2006; ISO 14044, 2006). The database selected for building the inventory was (EcoInvent, 2015).

Due to the current concerns regarding climate change, the method for environmental impact evaluation selected was IPCC GWP 100y (IPCC, 2013), which expresses the environmental impact in kg CO_2-equivalent (kg CO_2-eq) in a time horizon of 100 years. Emission metrics, such as Global Warming Potential (GWP), are used to quantify and communicate the relative and absolute contributions to climate change of emissions of different substances, and emissions from regions/countries or sources/sectors (Myhre et al., 2013).

The GWP of a gas, as established by the Intergovernmental Panel on Climate Change (IPCC, 2013), measures of how much energy the emissions of 1 kg of gas will absorb over a given time horizon, relative to the emissions of 1 kg of carbon dioxide (USEPA, 2016). The result of the effect is expressed in greenhouse gas (GHG) emissions, kg CO_2-eq (IPCC, 2013), which is a common unit of measure that enables the addition of emissions of different gases and allows for the comparison of opportunities to reduce emissions across sectors and gases (US EPA, 2016). Long time horizons (100 and 500 years) are used for cumulative effect, while short horizons of time (20 years) translate an indication of the short time effects of the emissions (IPCC, 2013).

2.2. Case study

The generator group studied was built at the Innovation Laboratory, at the Federal University of Paraiba (Northeast Brazil). The generator group is constituted by one 4-cylinder internal combustion engine (MWM reference 229), one Bambozzi 36 KVA generator and one resistor load bank, which simulates the system load (Fig. 1).

Fig. 1. Generator group

The structural changes implemented in the engine for biomass syngas operation were minimal and therefore not included in the LCA. The functional unit of the LCA, to which all inputs and outputs of the system were related to, was the production of 100 kWh of electricity. Diesel fuel and biomass syngas were utilized, at maximum (26 kW) and minimum (13 kW) powers.

The process selected for diesel fuel included the extraction of crude oil, production of diesel (all flows of materials and energy were accounted for, due to throughput of 1 kg of crude oil in the refinery. The multi-output process delivered the co-products petrol, unleaded, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphta, propane/butane, refinery gas, secondary sulphur, and electricity. The impacts of processing were allocated to the different products), and transportation of diesel from the refinery to the point of sale. Also included were the operation of storage tanks and petrol stations, along with emissions from evaporation and treatment of effluents.

Due to the location of the experimental setup (Paraíba state, Northeast Brazil), the most abundant available local biomass include woody residues and sugarcane bagasse. Availability of these for the gasification process is not an issue (Delgado et al., 2018). A disadvantage that should be mentioned is, obviously, the lower heating value of biomass in comparison with diesel fuel (approximately three times lower), resulting in the need of increased storage volumes. Sugarcane bagasse availability depends on the production schedules of the sugar and ethanol industry, and is usually utilized by the industries themselves in cogeneration schemes, displacing the utilization of fossil fuels. In cogeneration schemes, sugarcane bagasse can be used to produce heat and power that can be consumed locally or exported into the electric grid, depending on the legal requirements.

The idea supporting the utilization of wood chips (woody residues) is the availability of this indigenous resource in Northeast Brazil. Woody residues will be considered herein, following Delgado et al. (2018) and Araújo et al. (2018).

The process selected for woody biomass included the wood chips (mixed logs) and the conversion into synthetic gas. It includes drying (down to 10-15% moisture) and further comminution of wood chips (down to a size of 30x30x30 mm), fixed-bed gasification of the wood chips and treatment of the resulting syngas to remove impurities and contaminants.

A transportation distance of 10 km was considered for the diesel and biomass fuels, from point-of-sale to the laboratory. Table 1 shows diesel and biomass syngas consumption data at low and high powers, for the production of 100 kWh of electricity. For diesel consumption, data shown in Table 1 corresponded to 35.38 L/100kWh at minimum power and 35 L/100kWh at maximum power). For syngas, consumption corresponded to 508 m^3/100kWh at minimum power and 367 m^3/100kWh at maximum power).

For diesel, density was 0.85 kg/L, with 41.29 MJ/kg. Composition (% mol.) of the resulting syngas was 28.4% H_2, 40.6% CO, 23.6% CO_2, 5.9% CH_4 and 1.5% CnHm (mol.) on a nitrogen and water free basis (EcoInvent, 2015). Density of syngas was 1.15 kg/Nm^3, with lower heating value 5.2 MJ/Nm^3, and net gas yield 1.922 Nm^3/kg of wood (EcoInvent, 2015).

Table 1. Diesel and biomass syngas consumption data for the generation of 100 kWh electricity

	Diesel consumption (MJ)	***Syngas consumption (MJ)***
Minimum power (13 kW)	1241.59	2641.60
Maximum power (26 kW)	1228.38	1908.40

According to Table 1 data, the processes were implemented in Simapro® for analysis and comparison of fuels for the production of electricity.

3. Results and discussions

Due to concerns on climate change, this work has focused on GHG emissions. The damage caused by increasing GHG emissions includes (Allen et al., 2009; Christiansen, 2016; Lashof and Ahuja, 1990):

- elevation of the average global temperature, from 1.4ºC (optimistic) to 5.8ºC (pessimistic), for the period 1990-2100;
- increase in precipitation, especially in intermediate and high latitudes, simultaneously with a decrease in precipitation on low latitudes;
- possibility of reducing the arctic ice due to melting;
- possibility of the elevation of the average sea levels, from 0.09 m (optimistic) to 2.0 m (pessimistic), between 1990 and 2100, due to the melting of polar caps and continental icefields as well as thermal expansion caused by the increase in average global temperature.

Also, variations in precipitation and evapotranspiration affect water distribution differently across the globe, where some regions will experience increased water volumes and intensification of phenomena such as torrential rain followed by floods.

Global warming is a threat for human wellbeing and the world economy (Baylis et al., 2017; Beck, 2016; Fehr-Duda and Fehr, 2016; Gough, 2015; McMichael, 2013), and the Paris agreement is a milestone in the international negotiations of this century. The Paris agreement establishes that countries must reduce GHG emissions after 2020 (Rogeli et al., 2016; Savaresi, 2016; United Nations, 2015). Brazil has been taking a leading role in the Climate Convention negotiations, especially after 2009, when the country presents its National Policy on Climate Change (Brazilian law 12187/2009) and then the National Plan on Climate Change (Decree 7390/2010) (EULER, 2016). These regulation frameworks defined the Brazilian strategy of voluntary reduction of GHG (between 36.1% and 38.9% concerning emissions projected until 2020), and sector-specific action plans to reach such goals (EULER, 2016). Within the Paris agreement, Brazil indicates an even more ambitious commitment to reduce absolute emissions and eliminate illegal deforestation by 2030 (Azevedo et al., 2017; Gurgel and Paltsev, 2014). Table 2 presents information on the electricity production using diesel, demonstrating numerically the negative carbon footprint associated with the high emissions of CO_2-eq to the environment.

The main contributor to the final emissions was the use of diesel itself. Transportation of fuel to the generation site was expressed in tonne*kilometers: tkm, but this step presented a minimal contribution to the overall emissions, less than 0.15%. The majority of emissions (84%) were associated with the combustion of diesel; these operational emissions are a mixture of gases and fine particles; the primary pollutants are particulate matter, carbon monoxide, nitrogen oxides, hydrocarbons, and volatile organic compounds (Lloyd and Cackette, 2001). Table 3 shows data for the electricity production process, using biomass syngas as fuel. The transportation step of biomass was responsible for 2.7-4% of the final overall carbon footprint. When diesel was substituted by biomass syngas to produce 100 kWh of electricity, the carbon footprint was dramatically reduced, avoiding the emissions of 82.29 kg of CO_2-eq at minimum power and 88.42 kg of CO_2-eq at maximum power. Fig. 2 shows the carbon footprints for the four cases herein analyzed, normalized to the highest carbon footprint (diesel generation, low power). Fig. 2 shows that the overall carbon footprint associated with electricity generation could be reduced to less than 25% when biomass syngas is utilized.

Several studies have focused on the substitution of diesel: Figueiredo et al. (2012) obtained good performance of the generator set using syngas, without distortions in the quality of the generated energy. Udaeta et al. (2004) presented a comparison between diesel and biodiesel, concluding that diesel is favorable from technical-economic and political analyses, while biodiesel presented environmental and social benefits. Heller et al. (2004) demonstrated that electricity generation with willow energy crops led to significant reductions in emissions, compared to coal-based electricity production in the U.S.A. The emissions associated with electricity production with biomass energy crops were similar to using woody residues (and almost carbon neutral) and that the pollution prevented was comparable to other renewable energy sources (solar and wind) (Heller et al., 2004). Table 4 presents a comparison of the available results presented in the scientific literature. The use of biomass proved to be an alternative fuel with attractive characteristics for its use, avoiding emissions of approximately 88 kg CO_2-eq due to the substitution of diesel, per 100 kWh produced. Considering a lifetime of 25 years, and daily production of 260 kW, the substitution of diesel by biomass syngas can achieve avoided emissions (negative emissions) of 208.78 $\cdot 10^6$ kg CO_2-eq. Following Araújo et al. (2018), the municipality of João Pessoa collected 20,000 tonnes of urban pruning residues in 2015, which means that approximately 7.56 GWh could be generated at minimum power, or 10.47 GWh at maximum power, with the experimental setup herein studied.

Table 2. Carbon footprint associated with the production of electricity with diesel

		per 100 kWh			
	Process	***Amount***	***Emissions kg CO_2-eq***	***TOTAL kg CO_2-eq***	***kg CO_2-eq/kWh***
Minimum power (13 kW)	*Diesel*	1241.59 MJ	109	109.16	1.0916
	Transportation	0.3 tkm	0.156		
Maximum power (26 kW)	*Diesel*	1228.38 MJ	108	108.15	1.0815
	Transportation	0.29 tkm	0.151		

Table 3. Carbon footprint associated with the production of electricity with biomass syngas

		per 100 kWh			
	Process	***Amount***	***Emissions kg CO_2-eq***	***TOTAL kg CO_2-eq***	***kg CO_2-eq/kWh***
Minimum power (13 kW)	*Syngas*	2641.60 MJ	25.80	26.87	0.2687
	Transportation	2.10 tkm	1.07		
Maximum power (26 kW)	*Syngas*	1908.40 MJ	19.20	19.73	0.1973
	Transportation	1.20 tkm	0.533		

Table 4. Comparison of scientific literature data for electricity generation from diesel and biomass

		Carbon footprint, kg CO_2-eq./kWh_{elec}				
		This study	***Heller et al. (2004)***	***Cherubini et al. (2009)***	***Turconi et al. (2013)***	***Varun and Prakash (2009)***
Electricity generation	***Diesel***	1.0916 / 1.0815	Not applicable	0.72 – 1.08	0.530-0.900	Not applicable
	Biomass syngas	0.2687 / 0.1973	0.040–0.050 (Willow biomass energy crops)	0.055-0.230	0.0085-0.130 (Unspecified biomass)	0.078

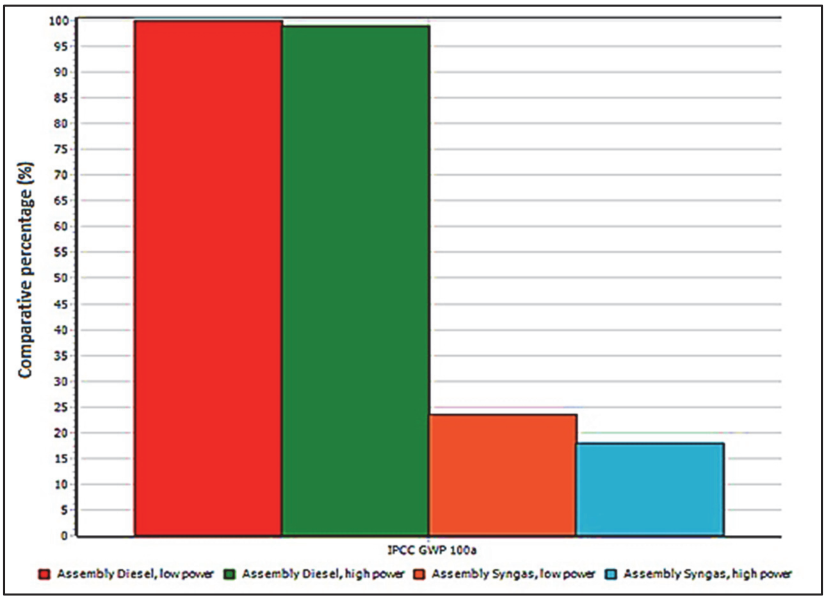

Fig. 2. Comparison of electricity generation carbon footprint, according to the utilized fuel.

4. Conclusions

The Life Cycle Assessment (LCA) methodology enabled the quantification of the carbon footprint associated with the utilization of two different fuels, diesel and biomass syngas, for the generation of electricity in an experimental generator.

Diesel fuel presented unsatisfactory results, emitting higher levels of greenhouse gases (1.092 kg CO_2-eq/kWh). Biomass syngas helped produce electricity more sustainably (0.269 kg CO_2-eq/kWh), evidencing a possibility of mitigating climate change, with overall avoided emissions of 0.823 kg CO_2-eq/kWh with fuel substitution. The utilization of biomass syngas as an energy resource can help contribute to the mitigation of climate change and can be used in Brazil to help fulfill its voluntary actions of reducing greenhouse gas emissions.

Mitigation of climate change was the primary concern investigated here in, although effects on human health could also have been selected and could have provided different results.

References

Allen M.R., Frame D.J., Huntingford C., Jones C.D., Lowe J.A., Meinshausen M., Meinshausen N., (2009), Warming caused by cumulative carbon emissions towards the trillionth tonne, *Nature*, **458**, 1163-1166.

Araújo Y.R.V., de Góis M.L., Junior L.M.C., Carvalho M. (2018), Carbon footprint associated with four disposal scenarios for urban pruning waste, *Environmental Science and Pollution Research*, **25**, 1863-1868.

Azevedo A.A., Rajão R., Costa M.A., Stabile M.C., Macedo M.N., dos Reis T.N.P, Alencar A., Soares-Filho B.S., Pacheco R., (2017*), Limits of Brazil's Forest Code as a means to end illegal deforestation*, Proc. of the National Academy of Sciences, **114**, 7653-7658.

BATS (2014a), Brazilian Association of Technical Standards, NBR 14040: Environmental management – Life cycle assessment – Principles and framework, Rio de Janeiro, ABNT.

BATS (2014b), Brazilian Association of Technical Standards, NBR 14044: Environmental management – Life cycle assessment – requirements and orientations, Rio de Janeiro, ABNT.

Baylis J., Owens P., Smith S., (2017), *The Globalization of World Politics: An Introduction to International Relations*, Oxford University Press, Oxford, UK.

Beck U., (2016), *The Metamorphosis of the World: How Climate Change is Transforming Our Concept of the World*, John Wiley & Sons.

Botelho C.A.V.D.A, (2012), *Technical feasibility and environmental aspects of ethyl biodiesel from frying waste oils* (in Portuguese), PhD Thesis, Universidade de São Paulo, São Paulo, Brazil.

Bravo Y., Carvalho M., Serra L. M., Monné C., Alonso S., Moreno F., Muñoz M., (2012), Environmental evaluation of dish-Stirling technology for power generation, *Solar Energy*, **86**, 2811-2825.

Bravo Y., Monné C., Bernal N., Carvalho M., Moreno F., Muñoz M., (2014), Hybridization of solar dish-stirling technology: Analysis and design, *Environmental Progress & Sustainable Energy*, **33**, 1459-1466.

Carvalho B.T.; Melo C.T.M.C.B., Figueiredo J.N., Carvalho M., (2017), *Multicriteria Optimization of the Energy Supply for a Northeast Brazil Hospital, Considering Solar Photovoltaic Energy*, 24th ABCM Intern. Congress of Mechanical Engineering, Curitiba, Brazil.

Carvalho M., Delgado D., (2017), Potential of photovoltaic solar energy to reduce the carbon footprint of the Brazilian electricity matrix, *LALCA-Revista Latino Americana em Avaliação do Ciclo de Vida*, **1**, 64-85.

Carvalho M., Lozano M.A., Serra L.M., (2012a), Multicriteria synthesis of trigeneration systems considering economic and environmental aspects, *Applied Energy*, **91**, 245-254.

Carvalho M., Lozano M.A., Serra L.M., Wohlgemuth V., (2012b), Modeling simple trigeneration systems for the distribution of environmental loads, *Environmental Modelling & Software*, **30**, 71-80.

Carvalho M., Millar D.L., (2012), Concept development of optimal mine site energy supply, *Energies*, **5**, 4726-4745.

Carvalho M., Serra L. M., Lozano M.A., (2011), Optimal synthesis of trigeneration systems subject to environmental constraints, *Energy*, ***36***, 3779-3790.

Cherubini F., Bird N.D., Cowie A., Jungmeier G., Schlamadinger B., Woess-Gallasch S., (2009), Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations, *Resources, Conservation and Recycling*, ***53***, 434-447.

Christiansen S.M., (2016), *Climate Conflicts - A Case of International Environmental and Humanitarian Law*, Springer International Publishing Switzerland.

Delgado D.B.M., Carvalho M., Chacartegui R., (2016), *Life Cycle Analysis as a Decision Criterion for the Implementation of Solar Photovoltaic Panels in a Northeast Brazil Hospital*, In *Energy, Transportation and Global Warming*, Grammelis P. (Ed.), Springer International Publishing, 13-20.

Delgado D.B.M., Carvalho M., Coelho Junior L.M., Chacartegui R., (2018), Analysis of biomass-fired boilers in a polygeneration system for a hospital, *Frontiers in Management Research*, **2**, 1-13.

Demirbas M. F., Balat M., Balat H., (2009), Potential contribution of biomass to the sustainable energy development, *Energy Conversion and Management*, **50**, 1746-1760.

EcoInvent, (2015) Base of dates, On line at: www.ecoinvent.ch.

Euler A.M.C., (2016), *The Paris Agreement and the Future of RED in Brazil*, In: *Climate Change: the Challenge of the Century*, Vicente M.C.P., (Ed.), Fundação Konrad Adenaeur, Rio de Janeiro, Brazil, 85-104.

Fehr-Duda H., Fehr E., (2016), Game human nature: finding ways to adapt natural tendencies and nudge collective action is central to the well-being of future generations, *Nature*, **530**, 413-416.

Figueiredo F.L., Fernandes F., Petrucci A.L., Filho R.F., Marsura M., (2012), Production of electricity through biomass in a concurrent gasification system and generator set with a capacity of 50 kVA, *Semina: Ciências Exatas e Tecnológica*, **33**, 165-174.

Gagnon L., Belanger C., Uchiyama Y., (2002), Life-cycle assessment of electricity generation options: the status of research in year 2001, *Energy Policy*, **30**, 1267-1278.

Gough I., (2015), Climate change and sustainable welfare: the centrality of human needs, *Cambridge Journal of Economics*, **39**, 1191-1214.

Guinee J.B., (2001), Life Cycle Assessment: An operational guide to the ISO Standards; LCA in Perspective; Guide; Operational Annex to Guide. Centre for Environmental Science, Leiden University, The Netherlands, On line at: https://pdfs.semanticscholar.org/83a8/8111da022a55b5045da17e5480ddaa754b26.pdf.

Guinee J.B., (2002), *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards,* Kluwer Academic Publishers, Boston, On line at: https://www.springer.com/gp/book/9781402002281.

Gurgel A.C., Paltsev S., (2014), Costs of reducing GHG emissions in Brazil, *Climate Policy*, **14**, 209-223.

Heller M.C., Keoleian G.A., Mann M.K., Volk T.A., (2004), Life cycle energy and environmental benefits of generating electricity from willow biomass, *Renewable Energy*, **29**, 1023-1042.

IEA, (2017), International Energy Agency, World Energy Balances: Overview, Paris: OECD/IEA, On line at: https://www.iea.org/statistics/balances/.

IPCC, (2013), Revised supplementary methods and good practice guidance arising from the Kyoto protocol, Intergovernmental Panel on Climate Change, On line at: http://www.ipcc-nggip.iges.or.jp/public/kpsg/.

ISO 14040, (2006), Environmental management - Life cycle assessment - Principles and framework, International Organization for Standardization, Genebra, On line at: https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en.

ISO 14044, (2006), Environmental management - Life cycle assessment - Requirements and guidelines, International Organization for Standardization (ISO), Genebra, On line at: https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en.

Lashof D.A., Ahuja D.R., (1990), Relative contributions of greenhouse gas emissions to global warming, *Nature*, **344**, 529-531.

Lloyd A.C., Cackette T.A., (2001), Diesel engines: environmental impact and control, *Journal of the Air & Waste Management Association*, **51**, 809-847.

Lozano M.A., Carvalho M., Serra L.M., (2014), Tackling environmental impacts in simple trigeneration systems operating under variable conditions, *The International Journal of Life Cycle Assessment*, **19**, 1087-1098.

McMichael A.J., (2013), Globalization, climate change, and human health, *New England Journal of Medicine*, **368**, 1335-1343.

Myhre G.D., Shindell F.M. Bréon W., Collins J., Fuglestvedt J., Huang D., Koch J.F., Lamarque D., Lee B., Mendoza T., Nakajima A., Robock G., Stephens T., Takemura and H. Zhang, (2013), *Anthropogenic and Natural Radiative Forcing*, In: *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker T.F., Qin D., Plattner G.-K., Tignor M., Allen S.K., Boschung J., Nauels A., Xia Y., Bex V., Midgley P.M., (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nel A., (2005), Air pollution-related illness: effects of particles, *Science*, **308**, 804-806.

Novelli V., Geatti P., Ceccon L., Toscani L., (2017), Low environmental impact of alternatively supplied cars. results of an investigation carried out in the north-east of Italy, *Environmental Engineering and Management Journal*, **16**, 1751-1759.

PréConsultants, (2015), SimaPro software, On line at: https://network.simapro.com/pre/.

Rogeli J., Den Elzen M., Höhne N., Fransen T., Fekete H., Winkler H., Schaeffer R., Sha F., Riahi K., Meinshausen M., (2016), Paris Agreement climate proposals need a boost to keep warming well below 2 C, *Nature*, **534**, 631-639.

Savaresi A., (2016), The Paris Agreement: a new beginning?, *Journal of Energy & Natural Resources Law*, **34**, 16-26.

Silva J.A.M., Santos, J.J.C.S., Carvalho M., de Oliveira S., (2017), On the thermoeconomic and LCA methods for waste and fuel allocation in multiproduct systems. *Energy*, **127**, 775-785.

Turconi R., Boldrin A., Astrup T, (2013), Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations, *Renewable and Sustainable Energy Reviews*, **28**, 555-565.

Udaeta M.E.M., Baitelo R.L., Burani G.F., (2004), *Comparison of Energy Production with Diesel and Biodiesel Analyzing all Costs Involved* (in Portuguese). Proc. of the 5th Encontro de Energia no Meio Rural, Campinas, Brazil.

United Nations, (2015), Paris agreement, On line at http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

USEPA, (2016), United States Environmental Protection Agency, Understanding Global Warming Potentials. 2016, On Line at: https://www3.epa.gov/climatechange/ghgemissions/gwps.html.

Varun B.I.K., Prakash R., (2009), LCA of renewable energy for electricity generation systems - a review, *Renewable and Sustainable Energy Reviews*, ***13***, 1067-1073.

Willers C.D., Rodrigues L.B., (2014), A critical evaluation of Brazilian life cycle assessment studies, *The International Journal of Life Cycle Assessment*, **19**, 144-152.