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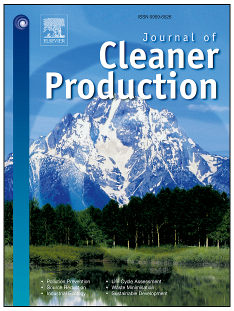

Environmental and energy performance of residual forest biomass for electricity generation: gasification vs. combustion

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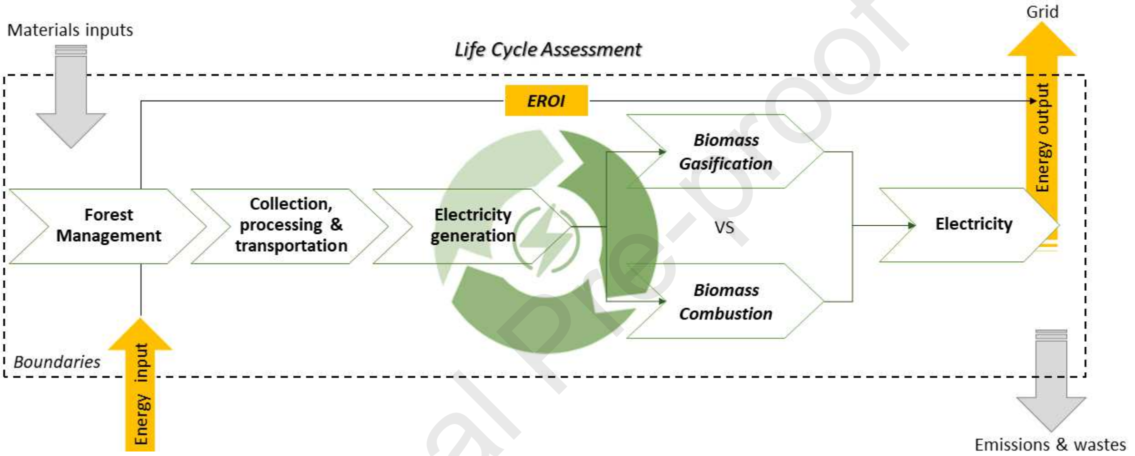
Abstract



Bioenergy systems have a great potential worldwide to substitute fossil fuels mainly because they may contribute to greenhouse gas emissions reduction. In Portugal, several biomass combustion-based power plants have been built in the last decade. Biomass gasification is a potential alternative to combustion but its environmental impacts should be evaluated. The goal of this study is to assess and compare the environmental and energy performance of direct gasification and combustion (both in fluidized bed) using residual forest biomass (RFB) from eucalypt in Portugal. In order to achieve the goal, life cycle assessment was applied, complemented with the Energy-Returned-On-Energy-Invested (EROI) indicator. The boundaries of the systems comprise three stages: (1) forest management, (2) collection, processing and transportation, and (3) electricity generation. The results indicate that gasification performs environmentally better than combustion in 5 out of 8 impact categories addressed. Conversely, combustion has greater EROI than gasification. After running a sensitivity analysis where the efficiency of the gasifier was changed from 53% in the base scenario to 57%, it is shown that the environmental performance of gasification improved in the range of 2 to 8%. The study concludes that gasification may be a good alternative to current combustion systems in Portugal.

Keywords: *Combustion, Electricity generation, Gasification, Life Cycle Assessment (LCA), Residual forest biomass.*

Abbreviations

LCA: *Life Cycle Assessment*

FU: *Functional Unit*

RFB: *Residual Forest Biomass*

PG: *Producer Gas*

GHG: *Greenhouse Gas*

FM: *Forest Management*

CTP: *Collecting, Transport and Processing*

EG: *Electricity Generation*

IGCC: *Integrated Gasification Combined Cycle*

CRC: *Combustion Rankine Cycle*

EROI: *Energy Returned On Energy Invested*

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1. Introduction

Nowadays, political and environmental strategies guide societies towards reducing the use of fossil fuels and hence greenhouse gas (GHG) emissions. Some of these strategies rely on the use of renewable energy sources instead of fossil fuels to produce either heat or electricity (REN21, 2020). Modern biomass (bioenergy)[1] is one of these renewable resources whose use has been increasing in recent years and it shares 5.1% of the total final energy consumption in 2018 (REN21, 2020). Among biomass resources, forest biomass is the most popular and largest contributor to the bioenergy mix globally, accounting for more than 85% of all biomass used for energy purposes (IEA, 2018; WBA, 2019).

Combustion is the most widely used process for the production of heat and electricity from biomass (Knoef, 2005; REN21, 2020). Gasification is a thermochemical conversion process alternative to combustion which converts solid biomass into a gaseous fuel through the reaction between the solid biomass and a gasification agent (air, oxygen (O_2) or steam water) at high temperatures (700-900°C). The gasification process can be classified according to the gasification agent and the heat required for the operation: a) direct and autothermal if the air or O_2 is the gasification agent used and if the process heat required is provided by partial combustion of the biomass or b) indirect and allothermal if steam water is the gasification agent and the heat is supplied from an external source (Jungbluth et al., 2007). The gaseous fuel produced often called producer gas is mainly composed of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and methane (CH_4).

The biomass gasification offers several advantages over combustion (Siedlecki et al., 2011) namely: i) the corrosion level is lower due to the lower temperature of the gases; the fuel throughput per unit area is higher, which means that smaller gasification units can process the same amount of fuel as larger combustions units, ii) gasifiers can convert the energy content of a feedstock to hot combustible gases at 85% to 90% thermal efficiency, iii) unlike combustion, the substances that cause

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[1] Modern bioenergy is any production and use of bioenergy that is not classified as traditional use of biomass. The latter involves the burning of woody biomass or charcoal as well as dung and other agricultural residues in simple and inefficient devices in developing and emerging economies (REN21, 2020)

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operational problems can be removed at relatively high temperatures through gas cleaning, without significant loss of sensible heat, and iv) this technique allows an easy adaptation to established energy conversion technologies (Bhavanam and Sastry, 2011; Knoef, 2005; Reed and Gaur, 2001; Sansaniwal et al., 2017).

In Portugal, several biomass combustion-based power plants have been built mainly in the last decade as a result of the National Energy Strategy (Conselho de Ministros, 2010) that set different targets of electricity generation from renewable sources until 2020, aiming to mitigate climate change, among other objectives. These power plants are mainly supplied by *residual forest biomass* (RFB), contributing this way for forest cleaning and consequently, for reducing the risk of forest wildfires which are of great concern in the country. A significant proportion of this RFB (47 to 58%) comes from eucalypt (*Eucalyptus globulus*) (Dias, 2014; Ferreira et al., 2017) which occupies the largest forest area in the country (845 thousand ha; 26 % of the forest area) (ICNF, 2015). To date there are not biomass gasification power plants in Portugal.

Although electricity production from forest biomass has environmental benefits, particularly to GHG emissions reduction, it has also potential environmental impacts that should be evaluated from a life cycle perspective. In this sense, for example, da Costa et al., (2018) applied life cycle assessment (LCA) to assess and compare the environmental performance of electricity production in Portugal from RFB combustion using two technologies: grate furnaces and fluidized bed furnaces. On the other hand, LCA has also been applied to quantify the environmental impacts of forest biomass gasification to produce electricity (Carpentieri et al., 2005; Siegl et al., 2011) or both heat and electricity (Cambero et al., 2015; Guest et al., 2011; Jäppinen et al., 2014; Puy et al., 2010; Steubing et al., 2011). However, the environmental impact results of these studies differ considerably depending on forest species, biomass moisture content, gasification efficiency and distance travelled to supply the biomass, as well as methodological choices such as system boundaries.

So far, no LCA study of gasification has been performed with biomass from eucalypt or other forest species commonly found in Portugal. Moreover, studies directly comparing forest biomass gasification with combustion for electricity generation from an environmental life cycle perspective are scarce and impacts greatly depend on

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specific conditions (e.g. forest management, transportation, biomass type and treatment, etc.) according to the literature reviewed (Cambero et al., 2015; Jäppinen et al., 2014; Siegl et al., 2011; Steubing et al., 2011). In this context, the objective of this study is to evaluate, from a life cycle perspective, the environmental and energy performance of electricity production from direct gasification of RFB from logging activities in Portugal, and to compare with the most common biomass-to-energy practice in the country (combustion). Thus, this study contributes to the assessment of the environmental and energy viability of the gasification process in relation to combustion, bridging the existing gap and contributing with knowledge to support future decision-making.

2. Methodology

The environmental performance of both gasification and combustion is evaluated using LCA in agreement with the ISO 14040 and 14044 standards (ISO, 2006a, 2006b) and SimaPro software (Version 8.5.0.0). Energy accounting is additionally carried out in order to determine the EROI of the systems.

2.1. Goal and scope definition

The goal of the study is presented in the Introduction section. Since electricity is the product output of the systems assessed, 1 kWh_e injected into the power grid is set as functional unit (FU). The gasification and combustion systems under analysis are shown in Figure 1. The system boundaries comprise the following stages: 1) forest management (FM), 2) collection, processing and transportation (CPT), and 3) electricity generation (EG) by combustion Rankine cycle (EG-CRC) or integrated gasification-combined cycle (EG-IGCC) that combines Brayton cycle plus Rankine cycle. FM and CPT are similar in both systems. Details of each stage are presented in Section 2.2. Regarding capital goods, the construction of power plants was included but their dismantling as well as machinery fabrication are excluded from the analysis.

Allocation is needed the FM stage because it generates wood, bark, stumps and logging residues (branches, tops and foliage). Allocation by mass is adopted according to Dias (2014) and assuming that half of the logging residues and stumps are considered to be left on the forest soil due to ecological, technical and logistical

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constrains. Therefore, no environmental burdens are allocated to these residues that remain in the forest soil because they are not an output of the system. The allocation factors are the same proposed by Dias (2014), based on Tomé et al. (2006): 75% for wood, 10% for logging residues, 10% for bark and 4% for stumps.

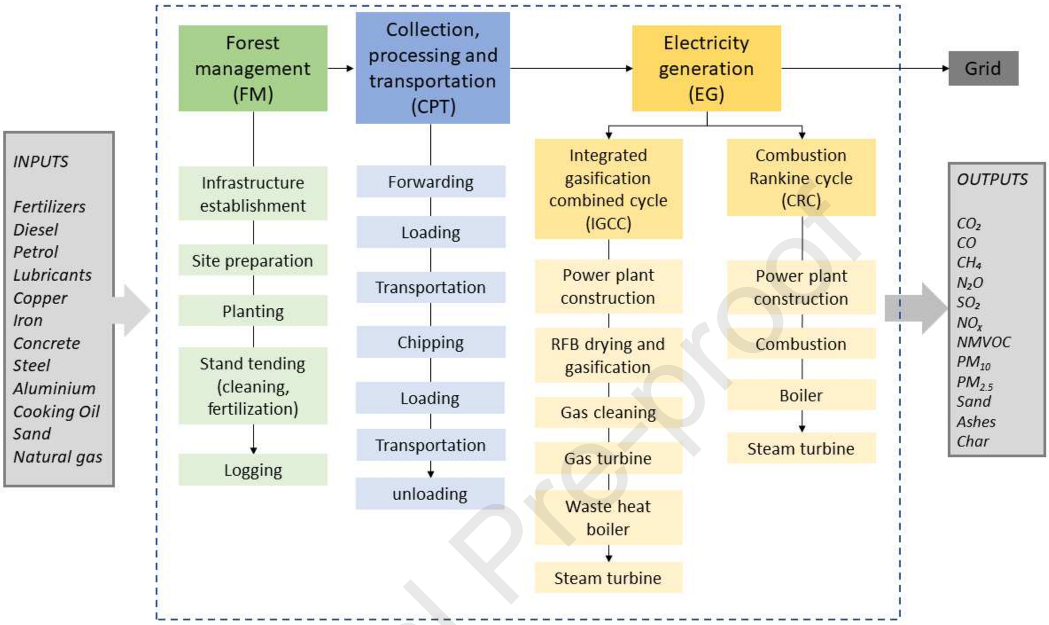

Figure 1. System boundaries of the gasification and combustion systems.

2.2 Life cycle inventory

2.2.1 Forest management stage

The FM stage includes several operations carried out in eucalypt forest during site preparation, planting, stand tending, logging and infrastructure establishment (road and firebreak building and maintenance), based on previous studies (Dias et al., 2007; Dias and Arroja, 2012). In this study, it is considered that biogenic CO_2 emissions are climate neutral-based on the principle that CO_2 released from gasification or combustion will be removed from the atmosphere by biomass regrowth (Cherubini and Strømman, 2011). The inventory data from the production of eucalypt biomass up to wood felling were taken from Dias and Arroja (2012), considering a high intensity management scenario following best practices, where felling is performed with an harvester. The inventory data of diesel, lubricant, and fertilizers production are retrieved from Ecoinvent database (Wernet et al., 2016).

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2.2.2. RFB collection, processing and transportation stage

This stage includes RFB forwarding, chipping at a terminal, loading/unloading operations and transportation from forest up to the EG-CRC and EG-IGCC power plants. The total distance covered is 35 kilometers of which 10 km are between forest and the chipping terminal, and 25 km are between the chipping terminal and the power plant. The eucalypt RFB is collected with a forwarder and is then transported by tractors with a semi-trailer to a terminal to be chipped. The chipped biomass is then loaded onto trucks and transported to the EG-CRC and EG-IGCC power plants. All operations mentioned above are described in detail in Dias (2014), as well as the corresponding inventory data. However, the presented study considers an average moisture content of 40% for the chipped logging residues accordingly to da Costa et al. (2018) instead of the original moisture content of 35%. Data on fuel production and transportation processes are taken from Ecoinvent database (Wernet et al., 2016).

2.2.3. Electricity generation stage

The EG stage includes both power plant construction and operation. In the ER-IGCC, the operation comprises RFB drying, direct (air) gasification in fluidized bed reactor, producer gas (PG) cleaning, gas turbine, waste heat recovery boiler and steam turbine (Figure 2). In the case of EG-CRC, it includes direct combustion in a bubbling fluidized bed reactor with a boiler and steam turbine. Detailed information regarding the mass-energy balance as well as the diagram of the EG-CRC can be seen in Supplementary Material.

Table 1 presents the construction materials considered for both power plant construction and their average values per MW_e installed. The inventory data of the construction materials production processes are taken from Ecoinvent database (Wernet et al., 2016). A lifespan of 25 years for the power plants was assumed (Cardoso et al., 2019). Both EG-IGCC and EG-CRC power plants have an installed capacity of 12.5 MW with an electrical efficiency of 19% and 22% respectively with a plant factor of 90%. Both the installed capacity and plant factor were based on an operating conditions of the EG-CRC power plant studied by da Costa et al. (2018).

Table 1. Life cycle inventory data for combustion and gasification power plant construction. Sources: Li et al. (2018); Thakur et al. (2014); Valero et al. (2018); Wang et al. (2014)

Material	Amount	Unit
Concrete[a]	159	
Iron	0.75	
Steel	50.0	t/MW_e
Copper	3.00	
Aluminum	0.50	

[a]Concrete density: 1800 kg/m^3. Compressive strength 25 MPa.

All the inventory data regarding the RFB direct gasification process were obtained from experiments carried out in a pilot-scale gasification installation running at the University of Aveiro, Portugal (Pio et al., 2017). However, data are scaled up in order to obtain the same power output of the EG-CRC power plant. At the pilot scale, the RFB is introduced in the gasification chamber by means of a screw feeder and is converted at an average temperature of 785 °C in a bubbling fluidized bed reactor of 80 kW_{th}, operated at atmospheric pressure and under auto-thermal regime, thus, direct gasification using atmospheric air. The bottom and fly ashes generated during biomass gasification, composed by particles from sand bed and ashes from the biomass (Pio et al., 2017), were considered to be disposed at a sanitary landfill. The gasifier thermal efficiency is 53%, leading to the production of 1.99 kg of PG from 1 kg of RFB. The operating conditions of the gasifier are shown in Table 2 while the elemental analysis and main properties of the RFB and PG are presented in Table 3 and Table 4. Natural gas was assumed to be used as auxiliary fuel in the same amount as in the EG-CRC operation.

Subsequently, the PG is cleaned through oil-based gas washer (OLGA) system (Figure 3), which consists on a multi-stage scrubber where oil is used as a cleaning agent (Boerrigter et al., 2005). To date, this system is the most efficient and effective among the existing producer gas cleaning systems (Abdoulmoumine et al., 2015; Anis and Zainal, 2011; Woolcock and Brown, 2013). OLGA allows removing particulate matter and tars from the PG which are later reintroduced into the gasifier. Oil consumption (make up to compensate losses) is considered to be 8.12 g (1% of the oil flow in the OLGA system) (Boerrigter et al., 2005; Nicolaou, 2016).

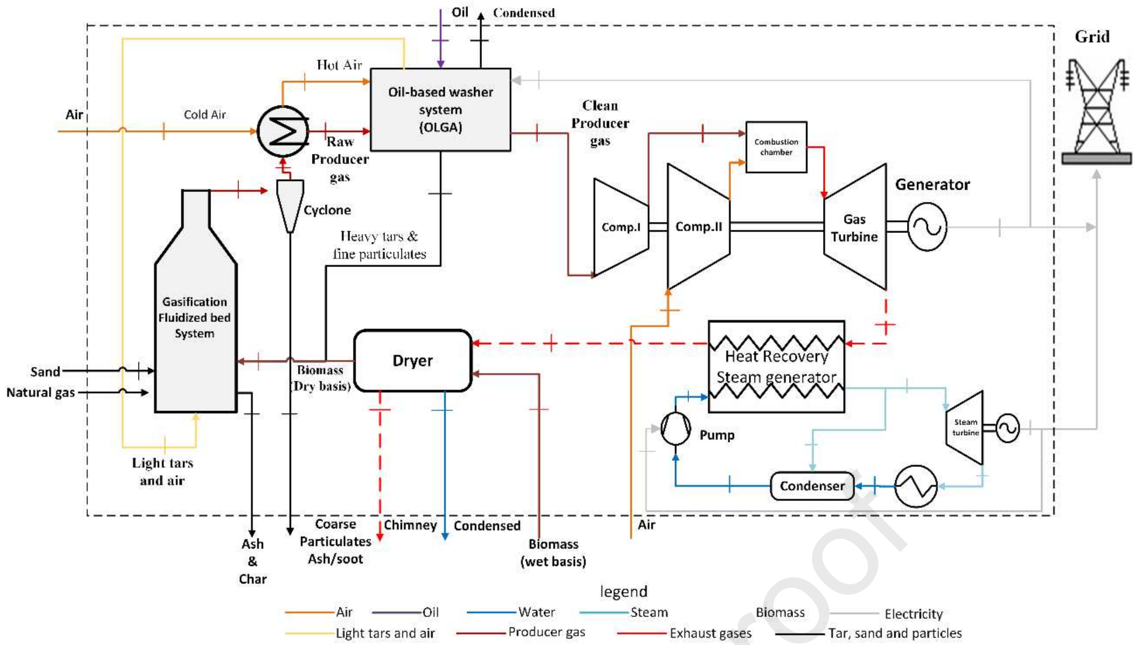

Figure 2. Diagram of the RFB integrated gasification combined cycle power plant

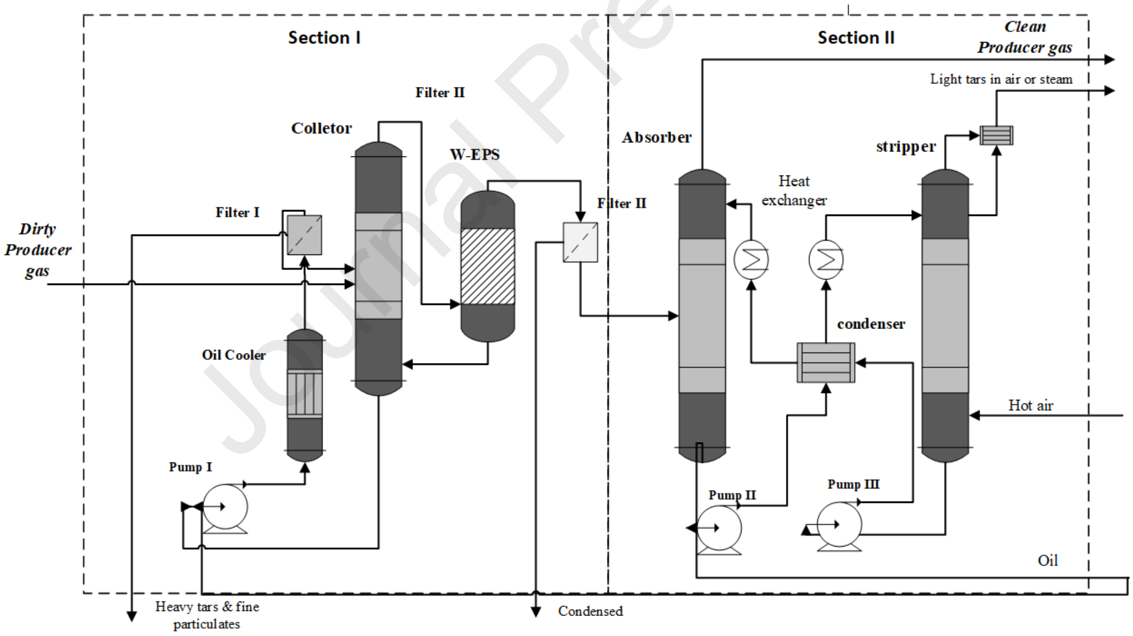

Figure 3. Diagram of the OLGA producer gas cleaning process. Source: (Boerrigter et al., 2005)

Table 2. Gasifier operation conditions. Source: Pio et al. (2017)

Parameter	*Value*	*Unit*
Average temperature	707.0	ºC
Dry producer gas yield	1.600	Nm^3/kg RFB (dry basis)
Average equivalence ratio	0.215	-
Carbon conversion efficiency	80.00	%
Cold gas efficiency	52.70	%

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Table 3. Chemical composition and lower heating value of RFB biomass. Source: Pio et al. (2017)

Parameter	Value	Unit
Elemental analysis		
C	0.459	kg/kg (dry basis)
H	0.061	
O	0.448	
N	0.004	
S	Nd[a]	
Proximate analysis		
Moisture	0.118	kg H_2O/kg
Ashes	0.028	kg/kg (dry basis)
Lower heating value	17.60	MJ/kg (dry basis)

[a] Not detected. A value of <100 mg/kg was considered (Silva et al., 2019)

Table 4. Producer gas characteristics. Source: Pio et al. (2017)

Parameter	Value	Unit
CO_2	0.154	kmol/kmol
CH_4	0.048	
CO	0.180	
H_2	0.064	
C_2H_4	0.020	
N_2	0.534	
Lower heating value	4.660	MJ/kg

Downstream the OLGA process, the cleaned PG is feed in the combined cycle, that is Brayton and Rankine cycle. Both thermodynamics cycles are theoretically modelled based on the principle of conservation of mass and energy. The efficiency of the equipment (turbines, boiler and dryer) is retrieved from commercial catalogs (EPA and CHP, 2015a, 2015b). The electrical efficiency (η, %) of the EG-IGCC is 19% and according to Equation 1 (Descamps et al., 2008):

$$\eta = \frac{(\dot{W}_{Gt}+\dot{W}_{St})-\dot{W}_{aux}}{\dot{m}_{RFB}\times LHV_{RFB}} \times 100 \qquad (1)$$

Where $\dot{W}$ is the net power output (J/s) of the gas (*Gt*) and steam turbine (*St*), and the power consumption (J/s) of the auxiliary components (*aux*); $\dot{m}$ and *LHV* are the mass flow (kg/s) and lower heating value (J/kg) of RFB respectively. Details of calculations including PG cleaning process are presented in Supplementary Material. Biogenic emissions to air of CO_2, CO, and production of ashes and char were estimated through stoichiometric balance. A carbon conversion efficiency of 80% in the gasifier and a combustion efficiency of 99% in the gas turbine was assumed. The majority of the carbon is distributed between emissions to air, ashes and char. The remaining amount of carbon is present in tars which are retained in the OLGA cleaning system and returned to the gasifier as already explained. Other biomass-based air emissions such as SO_2, CH_4, NO_x and $PM_{2.5}$, etc., are obtained from the literature (Guest et al., 2011, Loução et al., 2019). Emission factors from natural gas burning are sourced from da Costa et al. (2018). EG-CRC uses an electrostatic precipitator to reduce particulate emissions.

Table 5 summarizes the inventory data of the EG-IGCC operation process as well as those of the EG-CRC operation process which is retrieved from da Costa et al. (2018). Inventory data on the production of sand, oil, natural gas (start-up process) and disposal of solid wastes (sand, ashes and char) in sanitary landfill are taken from Ecoinvent database (Wernet et al., 2016) both in EG-IGCC and EG-CRC.

Table 5. Life cycle inventory of EG-IGCC and EG-CRC for the generation of 1 kWh_e

		EG-IGCC	**EG-CRC**
Inputs	***Unit***	***Value***	***Value***
Eucalypt RFB	kg (dry basis)	1.027	0.914
Natural gas	Nm^3	0.003	0.003
Sand	g	20.00	12.60
Used cooking oil	g	8.120	-
Outputs			
Products:			
Electricity	kWh_e	1.000	1.000
Air emissions:			
NO_x	g	0.343	2.680
N_2O	g	n/a	0.141
SO_2	g	0.0006	0.353
NMVOC	g	n/a	0.117
CH_4	g	0.004	0.016
CO_2, fossil	g	7.182	7.182
CO, fossil	g	0.005	0.694
PM_{10}	g	0.160	0.400
$PM_{2.5}$	g	0.030	0.281
Wastes:			
Sand	g	20.00	12.60
Ashes	g	28.75	81.40
Char	g	91.60	-

n/a: not available

2.3 Impact assessment

The life cycle impacts are modelled using ReCiPe 2016 Midpoint at the hierarchist perspective (Huijbregts et al., 2017), considering the following impact categories: Global Warming, Ozone Formation (Terrestrial Ecosystems), Fine Particulate Matter Formation, Terrestrial Acidification, Freshwater Eutrophication, Marine Eutrophication, Mineral Resource Scarcity, and Fossil Resource Scarcity. On the other hand, the EROI (dimensionless) is assessed as follows (Hall et al., 2014):

$$EROI = \frac{E_o}{E_i} \qquad (2)$$

Where E_o is the total energy delivered to society and E_i is the total energy invested in the capture and delivery of E_o (Hall et al., 2014), both in kWh. E_i *is* determined from the accounting of the use of direct energy (e.g. fuel for engines, see Supplementary Material, Table S5) and indirect energy (the one needed to make products such as concrete, fertilisers, etc.). In the case of fossil fuels, the amount of energy is estimated by considering their mass and lower heating values.

3. Results and discussion

3.1 Environmental impact assessment of gasification

This section presents and discusses in detail the results obtained for the gasification system, while the detailed analysis of the results of the combustion system can be found in da Costa et al. (2018). The total environmental impacts and the EROI for the production of 1 kWh_e are presented in Table 6 and the relative contribution of each stage to the total impact are illustrated in Figure 4. The results show that the FM stage is the main hotspot for Fine Particulate Matter Formation (41%), Terrestrial Acidification (54%), Freshwater eutrophication (40%) and Marine Eutrophication (99%). In the case of Freshwater and Marine Eutrophication impacts, the application of fertilizers rich in phosphorus and nitrogen (phosphate and ammonium sulphate) is the main responsible for these contributions. For both Fine Particulate Matter Formation and Terrestrial Acidification impacts, the main causes are SO_2 and NO_x emissions from the burning of petroleum-based fuels in mechanized forest operations.

The CPT stage plays a major role in Global Warming and Fossil Resource Scarcity impact categories with contributions of 48% and 51% of the total impact, respectively.

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This contribution is mainly due to CO_2 emissions in Global Warming and petroleum depletion in Fossil Resource Scarcity, both from diesel consumption in the CPT activities. Conversely, this stage (CPT) has small contributions to the impacts of Ozone Formation, Freshwater Eutrophication, Marine Eutrophication and Mineral Resource Scarcity. A more detailed analysis of the impacts of the FM and CPT stages is presented in Dias (2014).

The EG-IGCC stage has the largest impacts on Ozone Formation (57%) and Mineral Resource Scarcity (73%), and is also relevant for Freshwater Eutrophication (39%). In Ozone Formation, most of the impacts are related with NO_x emissions that arise mainly from producer gas combustion. The disposal of sand, ashes and char in municipal landfill is the cause of Freshwater Eutrophication impact of the EG-IGCC stage. Lastly, the largest contributions to Mineral Resource Scarcity are from steel and copper used in the construction of the power plant.

The EROI obtained for the EG-IGCC system is 3.63, based on a value of 0.27 for E_i. The relative contribution of the stages for E_i (55% from CPT, 30% from FM and 15% from EG) is similar to that of the Fossil Resource Scarcity impact category because the share of renewable resources in E_i is only 0.5%.

Table 6. Life cycle environmental impacts and EROI of RFB gasification (EG-IGCC) and combustion (EG-CRC) per FU (1 kWh_e)

Impact category	Unit	EG-IGCC	EG-CRC
Global Warming	g $CO_{2\text{-eq}}$	77.9	109.1
Fine Particulate Matter Formation	g $PM2.5_{eq}$	0.218	0.806
Ozone Formation	g NOx_{eq}	0.600	2.896
Terrestrial Acidification	g $SO_{2\text{-eq}}$	0.685	1.801
Freshwater Eutrophication	g P_{eq}	0.012	0.015
Marine Eutrophication	g N_{eq}	0.095	0.083
Mineral Resource Scarcity	g Cu_{eq}	0.059	0.057
Fossil Resource Scarcity	g oil_{eq}	23.78	20.39
EROI	-	3.634	4.238

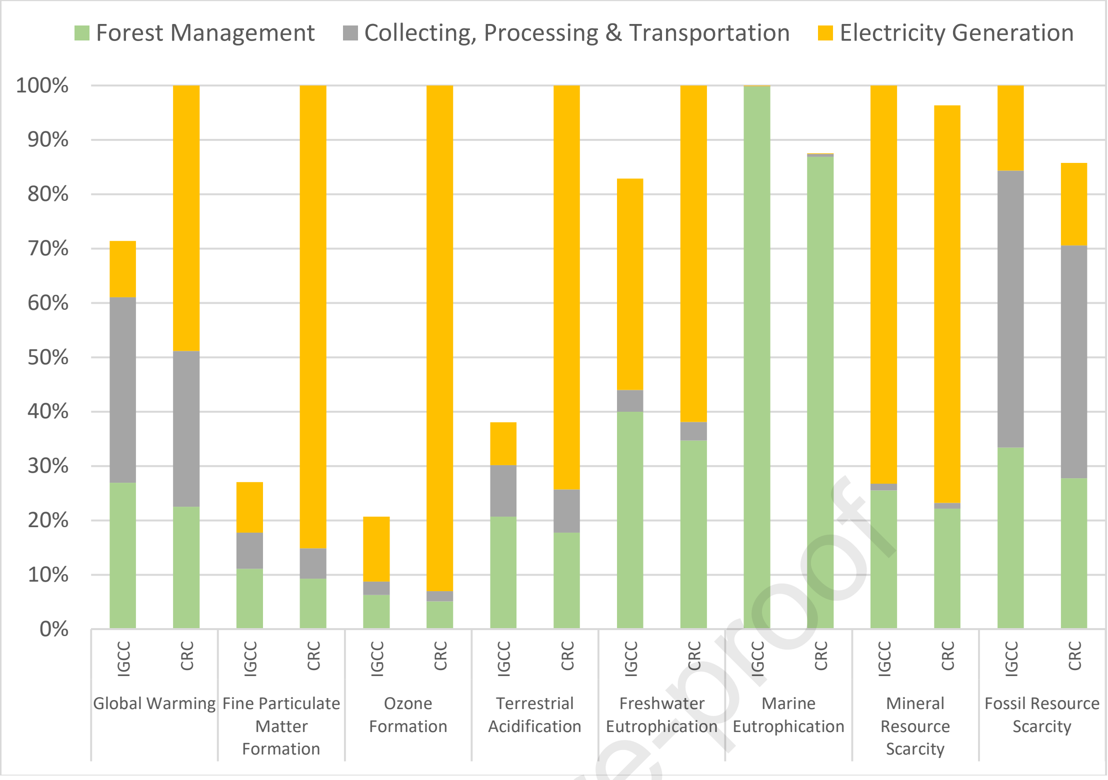

Figure 4. Environmental impact comparison between gasification (IGCC) and combustion (CRC) technologies (disaggregated into life cycle stages and considering 100% for the technology with the largest impact).

Table 7 summarizes the main features of biomass-based gasification case studies, showing that they vary widely due to differences in key parameters such as geographic location, biomass type, final product, and electrical efficiencies as well as in the methodological choices such as life cycle boundaries and impact assessment method. In the studies that evaluate only electricity production or provide impacts allocated to electricity, the life cycle GHG emissions are found to be in a wide range varying from 32 to 864 g $CO_{2\text{-eq}}$/kWh_e. Therefore, a comparison of the results with those from other studies should be conducted with caution.

For the purpose of a fair comparison, the results obtained in this study are compared with those reported by Guest et al. (2011) that evaluates RFB as the current study and only for the GW impact category. Although Puy et al. (2010), Jäppinen et al. (2014) and Cambero et al. (2015) also studied gasification of RFB, a comparison is not possible since they do not distinguish between the impacts of thermal and electric energy production and, in addition, Cambero et al. (2015) do not report the Global Warming impact per amount of energy produced. Guest et al. (2011) obtained a Global Warming impact of 32-40 g $CO_{2\text{-eq}}$/kWh_e which is smaller than that obtained in the current study but in the same order of magnitude. Possible reasons for such difference may be the electrical efficiency (up to 50% greater in Guest et al. (2011)) and the mix of residues considered. They studied gasification of a mix of residues from sawmills (10-30%) and forest (70-90%) supplied to micro (0.1 MW), small (1 MW) and medium (50 MW) internal combustion power plants for heat and electricity generation. The operation of the power plants was the largest contributing process to the GW impact (49-63% to the total impact) mainly due to the air emissions of N_2O. In the present study, that stage is not relevant.

Lastly, only the study of Zang et al. (2020) calculated the EROI of the biomass gasification systems under analysis. For the power generation system configuration similar to the one presented in this study, the EROI is 11% higher (4.10). In overall terms, the EROI of bioenergy systems is found to be ranging from 1 to 13 (Hall et al., 2014; Steubing et al., 2011; Weißbach et al., 2013) which is in agreement with the EROI obtained in the present study.

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Table 7. Literature review on life cycle GHG emissions of biomass gasification for electricity generation

Study	Carpentieri et al. (2005)	Puy et al. (2010)	Siegl et al. (2011)	Guest et al. (2011)	Steubing et al. (2011)	Nguyen et al. (2013)	Jäppinen et al. (2014)	Wang et al. (2014)	Paengjuntuek et al. (2015)	Cambero et al. (2015)	Yang et al. (2018)	Zang et al. (2020)
Geographic location	Not specified	Spain	Austria	Norway	Switzerland	Denmark	Finland	China	Not specified	Canada	China	Not specified
Biomass type	Poplar	Wood waste, forest residues	Wood chips	Forest and sawmill residues	Forest wood	Wheat straw	Forest wood, residues and Stumps	Straw	Rice straw	Sawmill chips, forest residues	Rice husks straw	Pine wood
System boundaries	Not specified	Biomass pre-treatment, transportation and gasification	Biomass production, transportation, power plant construction, operation and demolition; use/disposal of co-products.	Silviculture, harvesting, bundling, transportation, chip production, energy conversion	Wood growth, harvesting, transportation, gasification, pipeline transport	Removal, collection, pre-processing, energy conversion	Harvesting, fertilization, forwarding, transportation, storage, energy conversion	Planting, collection, storage, transportation, plant construction, operation, demolition and recycle	Extraction, transportation and manufacturing	Harvesting, transportation, collection, sawmill operation, energy conversion	Agricultural production, transportation, power plant construction, operation, maintenance, wastewater treatment	Forest management, biomass plantation, feedstock harvest, transportation, power plant construction, energy conversion, power plant decommission
Impact assessment method	Eco-indicator 95	CML 2001	CML 2001	CML 2001	Eco-indicator ’99, CML 2001	EDIP 97, Impact 2002+	IPCC	Not specified	IPCC, CML 2001	Impact 2002	Hybrid	CML 2015
Electrical efficiency	34%	28%	30%	24-38%	57%	36%	25%	25%	59%	29%	Not specified	Not specified
Final products	Electricity	Heat and electricity	Electricity	Heat and electricity	Heat, electricity and transportation fuel	Heat and electricity	Heat and electricity	Heat, electricity and cooling	Electricity	Heat and electricity	Electricity	Electricity
g $CO_{2\text{-}eq}/kWh_e$	178	871[a]	90	32-40	Not specified	77	8-33[A]	58	864	Not specified	493	209[B]

[A] These results refer to the production of 1 kWh of thermal and electric energy. [B] For the Air Gasification, internal combustion power generation system configuration.

3.2 Sensitivity analysis

The results presented in Section 3.1 are based on an average gasifier thermal efficiency of 53% (defined as cold gas efficiency, Pio et al. (2017)). However, higher thermal efficiency can be achieved according to experimental results of Pio et al. (2017). Other studies also show that the efficiency of the gasifier is usually in the range of 60 to 80% (Makwana et al., 2015; Tzeng Lim and Alimuddin, 2008; Xue et al., 2014), although it depends on the biomass feedstock (Makwana et al., 2015; Pio et al., 2017). In this context, a sensitivity analysis is performed considering the maximum thermal efficiency achieved (57%) during the gasification experimental results of Pio et al. (2017).

As expected, there is an improvement of the environmental performance in all impact categories addressed, compared with the base scenario (Figure 5), in the range of 2 to 8%. The maximum impact reduction is achieved in Marine Eutrophication, Global Warming, Fossil Resource Scarcity and Terrestrial Acidification, for which the total contribution of the FM and CPT stages is particularly high and, consequently, the effect of reducing biomass consumption and related impacts is higher. On the other hand, the minimum impact reduction is obtained in Mineral Resource Scarcity, Freshwater Eutrophication and Ozone Formation for which the effect of decreasing biomass consumption is smaller due to the low relevance of the FM and CPT stages. Lastly, an electrical efficiency of 21% and an EROI of 3.86 are achieved.

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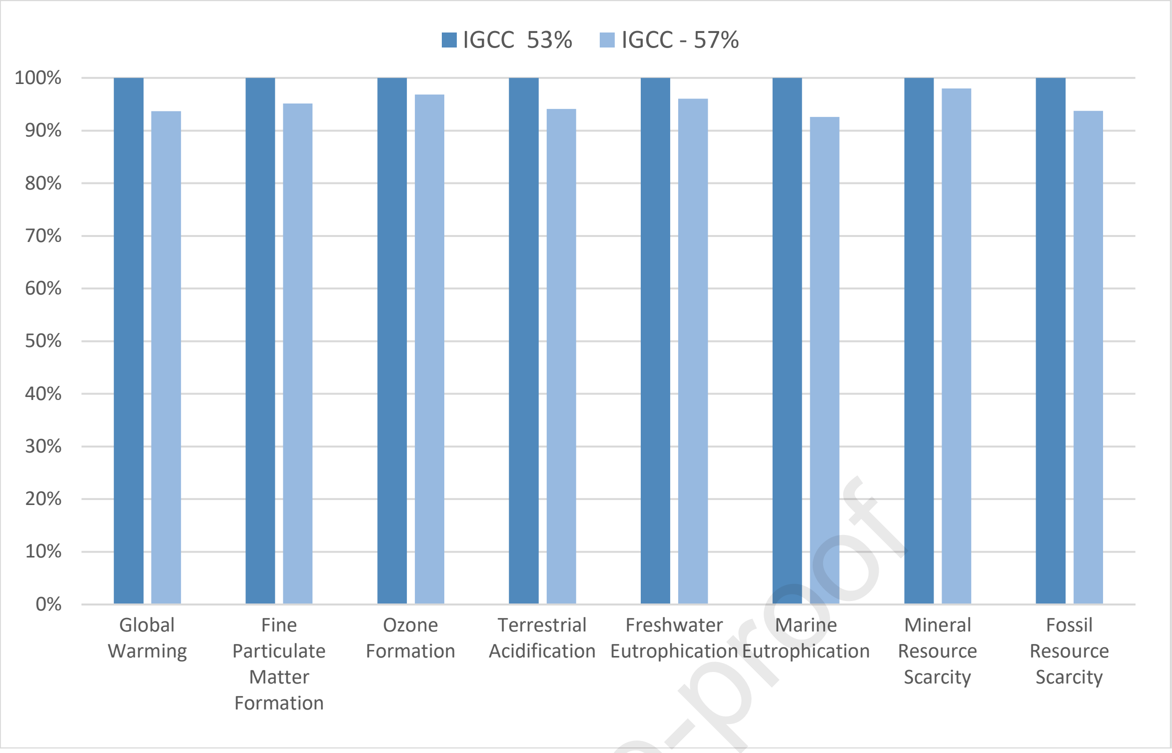

Figure 5. Results of the sensitivity analysis of gasification efficiency improvement (EG-IGCC 57%) and comparison with the base scenario (EG-IGCC 53%)

3.3. Gasification *versus* combustion

The comparison between the total impacts obtained for the two technologies (Table 6 and Figure 4) shows that gasification performs better than combustion in 5 out of 8 impact categories addressed. The difference in the impacts is higher for Ozone Formation (79%), Fine Particulate Matter Formation (73%) and Terrestrial Acidification (62%), but is also relevant for Global Warming (29%). Although gasification consumes 11% more RFB (dry basis) than combustion to produce 1 kWh_e, which implies slightly larger impacts in the FM and CPT stages, combustion presents higher impacts in the EG stage for these impact categories. Most of the impacts in the EG-CRC stage are explained by higher emissions of NO_x (in Fine Particulate Matter Formation, Ozone Formation and Terrestrial Acidification) and SO_2 (in Fine Particulate Matter Formation and Terrestrial Acidification) and the occurrence of emission of N_2O (in Global Warming) (Table 5). The high temperatures reached in the EG-CRC promotes especially the formation of nitrogen-oxides compounds. On the other hand, EG-IGCC has the advantage of applying a producer gas cleaning system that decreases the emission of such compounds in the combustion of the producer gas. In the case of the Freshwater

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Eutrophication impact category, the higher impacts of EG-IGCC are caused by the use of landfill where ashes and char are disposed.

Conversely, combustion has lower impacts on Marine Eutrophication (13%), Mineral Resource Scarcity (4%) and Fossil Resource Scarcity (14%), but the percentual reductions are smaller than those obtained for gasification in the remaining impact categories. In ME, the FM stage has 99% of the total impact for both technologies but the lower RFB consumption to generate 1 kWh_e in combustion leads to lower impacts. The FM stage also explains the difference in Mineral Resource Scarcity impact category. Lastly, in Fossil Resource Scarcity the difference in the impacts come from the smaller impacts of the FM and CPT stages in combustion. Even if the electrical efficiency of the gasifier would increase to 57% as considered in the sensitivity analysis, combustion would perform better than gasification for these impact categories, but the differences would be even smaller: 7% for Marine Eutrophication, 2% for Mineral Resource Scarcity and 6% for Fossil Resource Scarcity. Moreover, combustion obtained an EROI 17% greater than gasification due to higher efficiency and consequently lower fossil fuel consumption mainly in the CPT stage.

Combustion and gasification of biomass for producing electricity have been compared in previous LCA studies. However, in some of them a direct comparison is not provided as the main objective was to compare bioenergy alternatives in relation to a baseline (e.g. Cambero et al., 2015; Jäppinen et al., 2014; Steubing et al., 2011). Siegl et al. (2011) compared combustion and gasification of wood chips for electricity production and concluded that gasification only performs better in 2 (abiotic depletion and ozone depletion) out of 11 impact categories. The operation plant stage mainly made the difference between both technologies. Besides the efficiency, engine technology and flue gas cleaning system (multi cyclone and electrostatic precipitator) play an important role in the final results. Nguyen et al. (2013) also directly compared gasification and combustion but using straw as feedstock for producing both electricity and heat. They concluded that gasification appears to be more environmentally friendly than combustion mainly due to higher efficiency, lower level of emissions and higher amount of carbon retained in the ash. Bearing in mind the comparisons made, it is clear that each case has his own particular characteristics and conditions (e.g.,

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feedstock, engine technology, efficiency) which hampers deciding on one technology over another without knowing those characteristics and conditions.

4. Conclusions

This study aimed at assessing the environmental and energy performance of gasification of RFB for electricity generation in Portugal, from a life cycle approach. Moreover, gasification was compared with combustion technology. From the environmental perspective, the results for gasification show that the hotspot stages depend on the impact category: the FM stage is dominant for Fine Particulate Matter Formation, Terrestrial Acidification, Freshwater Eutrophication and Marine Eutrophication; the CPT stage is dominant for Global Warming and Fossil Resource Scarcity; and the EG stage is dominant for Ozone Formation and Mineral Resource Scarcity. What is more, gasification obtained an EROI of 3.63. Compared with combustion, gasification performs environmentally better than combustion in 5 (Global Warming, Fine Particulate Matter Formation, Ozone Formation, Freshwater Eutrophication and Terrestrial Acidification) out of 8 impact categories addressed, achieving reductions in the order of 17-79%. The main reasons for these differences are the higher air emission and ash production rates in the combustion process. In contrast, combustion is environmentally better in the remaining 3 impact categories, but with smaller differences (4-14%). In addition, its EROI is 17% higher (4.24) than gasification. The key factor for this better environmental-energy performance is the higher electrical efficiency of the combustion power plant. In conclusion, gasification seems to be a promising technology to be implemented as alternative to combustion for electricity generation from an environmental point of view, but the efficiency of the gasifier should be improved. Further research should be focused on evaluating other feedstocks, and technological and operational conditions, as they affect the environmental and energetic performance of both gasification and combustion systems.

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Highlights

- Environmental-energy assessment of electricity production from residual forest biomass.
- Gasification and combustion are compared from life cycle approach.
- Gasification has better environmental performance in 5 out of 8 impact categories.
- Combustion presents better EROI than gasification

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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