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Exergy and Environmental Analysis of the Substitution of Coal for Biomass in Thermal Power Plants in Brazil

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Abstract:

In the last decade, biomass consumption for thermal and electrical energy generation presented significant growth, as part of the plan to reduce greenhouse gas emissions through the gradual substitution of fossil fuels for renewable sources. In Brazil, although coal burning is still allowed in thermal power plants, the environmental demand is imminent for its substitution for less polluting sources and financial institutions already take a stand against coal investments, rising the pressure over existing consumers. This paper intends to identify and model coal-based power generation plants and compare its performance to that of different types of biomass available in Brazil – wood chips, wood pellets, sugarcane bagasse pellets – which are candidates to substitute coal in a large scale. Energy and exergy approaches are used to assess the full life cycle efficiency of these fuels, with a focus on the fuel combustion for steam generation, enabling the identification of inefficiencies and the selection of the most interesting operational opportunities. Despite of the life cycle specific energy consumption of biomass being higher than that of coal, its environmental performance is highly advantageous, drastically reducing fossil CO_2 emissions in the combustion process. When comparing pellets to dry wood chips, under the aspect of life cycle specific energy, biomass pellets result in a significantly higher specific energy consumption compared to dry wood chips, due to the thermal energy demand of drying and pelletizing stages. Such distinction between the performance of different types of low moisture biomass may only be detected if the life cycle approach is utilized. From the perspective of life cycle energy efficiency, the use of less processed types of biomass such as dried wood chips is preferrable over pellets.

Keywords:

Biomass; Thermal power plants; Coal substitution; Exergy analysis.

1. Introduction

Climate changes have encouraged efforts worldwide to reduce greenhouse gas emissions through the gradual insertion of renewable energy sources in substitution of fossil fuels, among which coal stands out as a major emitter to be controlled.

Coal substitution is an alternative to the reform of existing coal-based power plants for controlling NOx and SOx emissions limits, which tends to be an expensive solution, or even to their shutdown. Required investment for NOx and SOx control might be prohibitive and force these plants to interrupt operation [1].

Large scale power plants in the European Union have stricter atmospheric emissions limits to attend in the current decade, as described in BREF – Best Available Techniques Reference Documents – regarding not only CO_2 emissions, but also NOx and SOx emissions. IEEFA [1] shows that, from a sample of 600 solid fuel based power plants with capacities higher than 50 MW, more than 43% are not in conformity with new limits for SOx (180-320 mg/Nm³) and 69% were considered in non conformity with new limits for NOx (150-175 mg/Nm³).

In that context, as it is reported by Escobar [2], since 2010 biomass consumption in the European Union has presented significant growth. In opposition to the intermittent behavior of solar and wind-based power generation, biomass is adequate as a fuel for base load power plants.

In the United Kingdom, for instance, Drax power plant is one of the largest base load units, with an installed capacity of 4.0 GW, originally coal-based. From this total, approximately 2.6 GW have been converted to burn biomass pellets, which are mostly wood-based and imported from North America [3]. Other examples of

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coal to biomass conversions are reported by boiler manufacturers and contractors such as Mitsubishi Power [4], Hofor [5] and AET [6], which also list well succeeded conversions in Denmark, Finland and Canada.

By sharing physical characteristics with coal, biomass might be applied in existing coal-based power plants after adaptations in the fuel storage and combustion systems, which would result in a significant impact in the Brazilian electricity matrix. Although mineral coal represents a small fraction of the Brazilian matrix, it causes the highest specific CO_2 emissions for each MWh of generated electricity [7].

The Brazilian electricity matrix currently reports 6 operational coal-based pure power plants, with capacities ranging from 350 MW to 720 MW, and 3 coal-based cogeneration plants, with capacities from 75 MW to 104 MW [8], [9]. These plants are concentrated in the southern region, for which coal is mainly provided by national mines, and in the northern coast, for which coal is imported from Colombia and the USA.

At least since 2009, there have been reports pointing out that coal substitution or co-firing with biomass would be a promising alternative for clean electric generation in Brazil [10], but until this time there have not been yet registers of coal-based cogeneration or pure power plants to have firmly migrated to biomass. In the meantime, however, the potential of utilizing biomass for energy purposes has been extensively reported, usually highlighting *Eucalyptus* chips or pellets [2], [11], sugarcane bagasse pellets [12], [13] and straw pellets derived from many sources, such as rice, soy and corn [11].

The objective of this work is to compare the processes of electricity generation by coal combustion and biomass combustion, in several forms, in order to identify and quantify the potential of utilizing biomass as an energy source to substitute coal. This analysis uses energy and exergy approaches to evaluate the performance of the technological route for each fuel, as well as calculating CO_2 emissions resulting from their life cycle. This study should assess what are the impacts of substituting coal for biomass and what are the resulting efficiencies in each case.

2. Materials and methods

The simulations of typical thermal power plants are carried out in PowerFNESS® software [14], which contains a thermodynamic database for the working fluids used in power cycles and acts as an equation solver for mass and energy balances, given the inputs for equipment efficiencies and operational boundary conditions (flow, pressure and temperature).

The software is based on the construction of thermal cycles consisting of equipment, nodes and lines. The nodes represent boundary conditions and the union or separation of flow currents; in each node, fluid properties are calculated and updated on every simulation step. The lines serve as connections between nodes, which correspond mainly to the pipe sections and connections from the real system. When running the model, mass and energy balance equations are linearized and solved by the finite element method, until convergence to a steady state flow condition is reached.

A model description is presented in the following sections.

2.1. Process modeling

Typical plants for power and heat cogeneration or pure power generation are presented in Figure 1. Energy and exergy efficiencies will further be calculated based on these configurations.

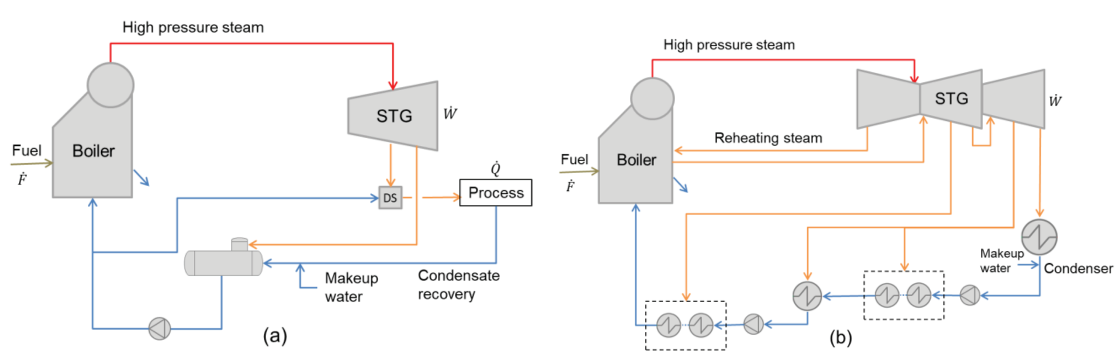

Figure 1. Thermodynamic cycles for power generation plants: a) Cogeneration of power and heat; b) Pure power generation.

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Table 2. Main operation parameters for cogeneration and pure power generation configurations.

Process parameter	**Unit**	**Cogeneration Plant**	**Pure Power Plant**
Boiler			
Type	-	Circulating Fluidized Bed / Pulverized Fuel	Pulverized Fuel
Operating steam pressure	bar a	85	170
Operating steam temperature	°C	485	540
Thermal efficiency	%	91	93
Turbogenerator			
Exhaust steam pressure	bar a	15	0.085
Thermal efficiency	%	84	86
Generator / Reductor losses	%	3	2
Process heat demand			
Steam flow	t/h	500	-
Steam pressure	bar a	15	-
Steam temperature	°C	210	-
Condensate Recovery			
Recovery rate	%	90	100
Temperature	°C	100	43
Makeup water			
Temperature	°C	25	25

Since 2 out of the 3 coal-based cogeneration plants listed by the Brazilian National Electric Power Agency are part of alumina refineries [8-9], in the Cogeneration scenario it is assumed that the process demands low pressure steam at 15 bar a, as this is representative of such refineries [15].

Regarding the boiler technology, typical configurations for Brazilian coal-based plants considered in this study are equipped with pulverized coal boilers, whose full conversion to biomass is arguably viable and has been applied in the previously mentioned cases [4], [5], [6]. The same premise could not be adopted for fluidized bed or grate boilers. Biomass has lower carbon content than coal, therefore producing less CO_2 in combustion, which is a gas that highly contributes to radiation heat exchange. Since grate boilers are the most dependent on radiation heat exchange, their performance would be the most harmed after fuel migration. Also, good performance in fluidized bed boilers is deeply related to fuel ash content, which is much lower for most types of biomass when compared to coal. Fluidized bed boilers that were originally designed to burn coal, exclusively, would hardly be able to maintain design bed temperature and achieve design capacity after the conversion to biomass.

2.2. Fuel characterization

Both *Eucalyptus* and sugarcane bagasse derived fuels are selected as substitute fuels for coal, given their abundancy as residues and potential to be grown in large scale sustainable forest plantations [2], [11].

Elemental compositions and moisture content for each fuel are presented in Table 2.

Table 2. Elemental composition of the selected fuels (dry basis).

Element	**Coal**	***Eucalyptus* *[16]***	**Sugarcane bagasse [16]**
C	72.7%	47.5%	46.5%
H	4.4%	6.1%	6.2%
N	1.1%	1.5%	1.2%
O	8.0%	43.8%	44.4%
S	2.4%	0.0%	0.0%

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Ashes	11.4%	1.1%	1.8%
Moisture	12.0%	15.0% (dry chips) 7.0% (pellets)	7.0% (pellets)

Ambient conditions are $T_0 = 25$ °C and $p_0 = 1$ bar.

Regarding fuel chemical exergy, Szargut [17] expressions for solid fuels are utilized, taking as inputs fuel LHV, moisture content and elemental composition:

$$b_{q,biom} = \beta.\left(LHV_{fuel} + x_w.h_{lv}\right) + x_w.b_{q,H2O,l} + x_S.\left(b_{q,S} - LHV_S\right) + x_{ash}.b_{q,ash} \tag{1}$$

Factor β varies according to mass composition of the respective fuel. The following correlations are established: any solid fuel, Eq. (2); coal, Eq. (3); wood, Eq. (4).

$$\beta = \frac{1.044 + 0.016(H/C) - 0.3493(O/C)[1 + 0.531(H/C)] + 0.0493(N/C)}{1 - 0.4124(O/C)} \tag{2}$$

$$\beta = 1.0437 + 0.1896\left(x_{H_2}/x_C\right) + 0.2499\left(x_{O_2}/x_C\right) + 0.0428\left(\frac{x_{N_2}}{x_C}\right) \tag{3}$$

$$\beta = \frac{1.0412 + 0.216\left(x_{H_2}/x_C\right) + 0.2499\left(x_{O_2}/x_C\right)\left[1 + 0.7884\left(x_{H_2}/x_C\right)\right] + 0.045\left(x_{N_2}/x_C\right)}{1 + 0.3035\left(x_{O_2}/x_C\right)} \tag{4}$$

From Eq. (1) to Eq. (4) and elemental compositions presented in Table 2, the chemical exergy for each fuel is calculated, as shown in Table 3, as well as the chemical exergy to LHV ratio.

Table 3. LHV and chemical exergy for each selected fuel.

Property	Unit	Coal	*Eucalyptus* dry chips	*Eucalyptus* pellets	Sugarcane bag. pellets
Moisture	%	12%	15%	7%	7%
Bulk density	kg/m³	900	350	657	726
LHV (per mass)	MJ/kg	25.6	14.8	17.2	18.3
LHV (per vol.)	MJ/m³	23040	5180	11300	13311
$LHV_{biomass}$ / LHV_{coal} (per vol.)	-	-	22%	49%	58%
bq	MJ/kg	28.4	15.7	18.0	19.1
bq/LHV	-	1.110	1.061	1.045	1.043

Aiming for operating the boilers at their original design capacities, substitute fuels shall have heating values and densities as close as possible to those of coal. The volumetric energy density of solid fuels has impacts both to the storage system design and to the boiler itself, whose furnace volume defines how much fuel can be introduced and how much heat can be generated. This hinders the utilization of *in natura* biomass at high moisture, due to its lower volumetric energy density. Dry wood chips at 15% moisture content were selected so that their LHV and density properties would be closer to pellets and coal. The necessary heat for drying wood chips from 40% down to 15% will further be considered in its life cycle analysis, as discussed in section 3.2. Wood chips would not serve as an alternative fuel for pulverized fuel boilers, but only for circulating fluidized bed boilers.

As presented in Table 3, all three types of biomass resulted in low values of chemical exergy to LHV ratio, ranging from 1.043 to 1.061, which is caused by their low moisture content. *In natura* wood chips with moisture content up to 40% would result in even higher ratios, up to 1.17, which would significantly harm the exergy efficiency of power plants.

Although dry wood chips and pellets are types of biomass with relatively high energy densities, they are still less dense than coal and would require the expansion of fuel storage, handling systems and the adaptation of burners, in the case of pulverized fuel boilers. Fuel silo (or bunker) and the pulverizing mill shall be adapted, as well as forced and induced air fans, since flue gas flow is expected to rise for higher moisture content fuels.

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2.3. Efficiencies

In cogeneration plants, both electric power and useful heat for process consumption are considered when calculating the plant efficiency, as shown in Eq. (5):

$$\eta_e = \frac{\dot{W} + \dot{Q}_u}{\dot{F}} \qquad (5)$$

In which:

- $\dot{W}$ is gross electric power
- $\dot{Q}_u = \dot{m}_{stm}(h_{stm} - h_{mup});$
- $\dot{F} = \dot{m}_{coal}.LHV_{coal}$ or $\dot{F} = \dot{m}_{bio}.LHV_{bio}$

In analogy, exergetic efficiency is calculated as in Eq. (6):

$$\eta_b = \frac{\dot{W} + \Delta\dot{B}_f}{\dot{B}_q} \qquad (6)$$

In which:

- $\dot{W}$ is gross electric power
- $\Delta\dot{B}_f = \dot{m}_{stm}(b_{stm} - b_{mup}) = \dot{m}_{stm}[(h_{stm} - h_{mup}) - T_0.(s_{stm} - s_{mup})];$
- $\dot{B}_q = \dot{m}_{coal}.b_{q,coal}$ or $\dot{B}_q = \dot{m}_{bio}.b_{q,bio}$

2.4. Life Cycle Analysis

2.4.1. Coal route

Figure 2 shows the most relevant stages in mineral coal life cycle, as well as resources consumed and gas effluents produced in each stage. As a premise in this study, only existing power plants will be evaluated, therefore both the plant construction and decommissioning are excluded from the routes considered.

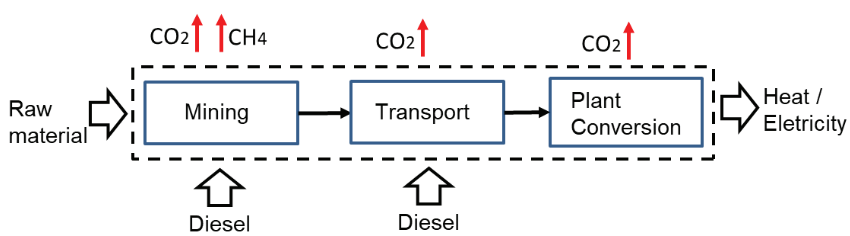

Figure 2. Mineral coal route to be consumed in existing power plants. Adapted from [18].

Figure 2 shows that, besides CO2 resulting from coal combustion and Diesel consumption in transportation vehicles, it is also relevant to count CH_4 emissions in mining stage. Methane is produced during coal formation process and is gradually liberated to the atmosphere as coal layers shatter and gas deconfines. Methane contribution in total equivalent CO_2 emissions equals 1% to 9% [18].

The tracking of mineral coal allows to calculate specific energy consumption rates and CO_2 emissions in terms of electric power generated as the final product of the power plant.

The following premises are considered [18]:

- Power plant life time: 30 years;
- Transportation logistics: road transport, 100 km radius;
- Equivalency from CH_4 to CO_2: 21 kg CH_4 / 1 kg CO_2 (100 year period);
- CH_4 contribution in total equivalent CO_2 emissions: 3%.

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2.4.2. Biomass route

Figure 3 shows the most relevant stages in biomass life cycle. After wood extraction and chipping, wet wood chips are dried to 15% before being transported to the power plants. Both for wood and sugarcane bagasse pellets, not only the material is dried, but also compacted to pellets. Besides Diesel consumption in extraction and transport stages before reaching to the power plant, drying and pelletizing stages also demand relevant heat and electricity.

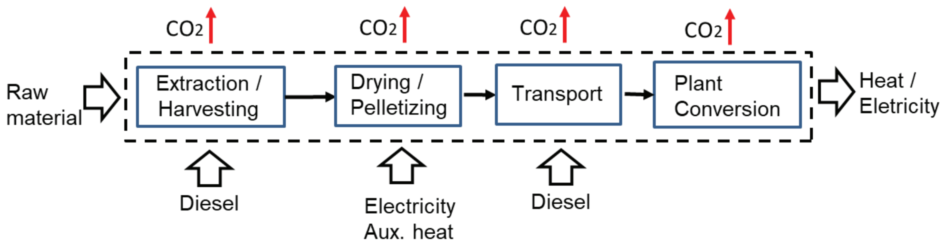

Figure 3. Biomass route to be consumed in existing power plants. Adapted from [19].

Premises for energy consumption and CO_2 emissions along biomass life cycle are the following [19]:

- Extraction executed by field harvesters, forwarders and chargers;
- Transportation logistics: road transport, 100 km radius;

As commented by [19], since silvicultural activities have a low level of mechanization compared to biomass extraction, harvesting and transport, then Diesel consumption at that stage is assumed to be not relevant to this analysis. Silviculture is therefore omitted from the biomass route illustrated in Figure 3.

3. Results and discussion

3.1. Thermal power plants

Table 4 shows the calculates efficiencies for each fuel and both plant configurations.

Table 4. Calculated efficiencies for each configuration.

Process parameter	Unit	Coal	Dry wood chips	Wood pellets	Sugarcane bag. pellets
Cogeneration Plant					
Fuel consumption	t/h	60.3	104.3	90.0	84.5
Fuel energy	MWh	430.2	428.8	429.8	429.7
Fuel exergy	MWh	475.5	454.9	449.2	449.1
Electricity generated	MWh	52.3	52.3	52.3	52.3
Steam to process	t/h	500.0	500.0	500.0	500.0
Thermal energy	MWh	338.5	338.5	338.5	338.5
Thermal exergy	MWh	136.6	136.6	136.6	136.6
Energy efficiency	%	90.9%	90.9%	90.9%	90.9%
Exergy efficiency	%	39.7%	41.5%	42.1%	42.1%
Pure Power Plant					
Fuel consumption	t/h	125.6	218.1	187.7	176.4
Fuel energy	MWh	896.6	896.6	896.6	896.6
Fuel exergy	MWh	991.0	951.2	937.2	936.9
Electricity generated	MWh	365	365.0	365.0	365.0
Energy efficiency	%	40.7%	40.7%	40.7%	40.7%
Exergy efficiency	%	36.8%	38.4%	38.9%	39.0%

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The calculated values shown in Table 4 refer to gross electric power generation and energy efficiency, therefore not considering impacts on electricity consumption by auxiliary systems within the power plants, such as fuel milling before pulverization or induced and forced draft fans. Although it is expected that the fans demand will increase due to higher flue gas flows resulting from wet biomass compared to coal, such impact would represent less than 0,1% of total power generation and may be neglected in this preliminary approach. Auxiliary systems electric load and general losses in a pulverized fuel fired power plant would typically represent up to 10% of gross electric power generation, therefore resulting in a net energy efficiency of 35% to 37% [18], which is consistent with the calculated gross energy efficiency of 40.7% as shown in Table 4. Analogously, exergy efficiency for pure power plants would be reduced to the range between 33% and 35% when net electricity generation is considered.

Impacts on boiler efficiency due to biomass moisture content were minimized in this study due to the selection of low moisture (<15%) types of biomass, but this would be a major factor in the case of *Eucalyptus* and sugarcane bagasse *in natura*, harming the efficiency and making it not viable to convert and still preserve the boiler design capacity.

From the exergy approach, the advantage is clear for the use of dry types of biomass instead of coal. As shown previously in Table 3, all three types of biomass with low moisture content resulted in close values of chemical exergy comparing their own LHV, which positively affects the exergy efficiencies. Energy and exergy losses due to the process of drying biomass are not detected in the thermal plant analysis, making it necessary to analyze the fuel life cycle to correctly quantify its influence.

Regarding the cogeneration configuration, exergy efficiencies are remarkably lower than energy efficiencies, as expected, since exergy approach calculates process steam as a low value stream, with low potential for electric power generation (15 bar a, 210°C).

3.2. Fuel life cycle

Coal and biomass life cycle performances are presented in Table 5. Each line shows the contribution of the most relevant energy sources consumed – Diesel (as fuel for extraction, handling and transportation vehicles), heat (for biomass drying), electricity – at specific energy consumption rates and equivalent CO_2 emissions along the fuel cycle from extraction stages to electricity conversion process.

Specific energy is calculated as the energy input to the energy output ratio, which is the inverse of the efficiency. The CO_2 emissions for coal and biomass life cycles are calculated according to [18] and [19], respectively, as the sum of direct, indirect and life cycle emissions.

Table 5. Calculated energy consumption and CO_2 emissions for each configuration.

Life cycle stage	Unit	Coal	Dry wood chips	Wood pellets	Sugarcane bag. pellets
Diesel					
Specific Energy	MJ/MWh	389	319	293	220
CO2 emissions	$kgCO_2/MWh$	28.2	22.4	21.2	16.0
Heat					
Specific Energy	MJ/MWh	0	969	1681	3778
CO_2 emissions	$kgCO_2/MWh$	0	0.3	0.5	1.1
Electricity					
Specific Energy	MJ/MWh	1590	766	571	403
CO_2 emissions	$kgCO_2/MWh$	2.2	1.1	0.8	0.6
Fuel					
Specific Energy	MJ/MWh	10073	10286	10286	10286
CO_2 emissions	$kgCO_2/MWh$	905.0	0.3	1.4	1.3
Total specific energy	MJ/MWh	12052	12340	12831	14687
Total CO_2 emissions	$kgCO_2/MWh$	935.4	24.0	23.9	18.9

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Energy consumption and equivalent CO_2 emissions due to fuel extraction and distribution stages highly depend on the characteristics of the mining area (in the case of coal) and the distances to the power plant sites. The premises presented in section 2.3 are estimations based on the main Brazilian power plants, but they should be revised when studying specific cases. In any respect, such values represent a small fraction of total energy and emissions, therefore not harming final conclusions here stated.

As Table 5 shows, biomass processing stage (chipping, drying, compaction) represents a significant fraction of total specific energy consumed, from 8% in the case of dry wood chips to 25% in the case of sugarcane bagasse pellets, resulting in higher values of total specific energy consumption than that of coal. Although an economical study is beyond the scope of this paper, it is relevant to mention that biomass processing also implies in higher production costs, which may inhibit the selection of dry versions of biomass. Conversions of this type will most probably take place in cogeneration and power plants which must preserve and guarantee the current heat and electric power generation capacities in the future scenarios. Otherwise, wet versions of wood and sugarcane bagasse would be acceptable, even if requiring an expansion in the storage area or causing derating in the boiler thermal capacity.

Both for coal and biomass, the energy conversion stage is dominant in the life cycle, representing from 70% to 84% of total energy consumption. This indicates that the biggest efforts to achieve higher efficiencies should be focused on this stage, through the correct evaluation and selection of the burner technology, biomass properties and operation routines.

In contrast to the energy efficiency performance, the environmental performances of all three types of biomass show significant benefits when compared to coal performance. Table 5 shows that wood chips, wood pellets and sugarcane bagasse pellets emit from 19.0 to 24.0 equivalent kg CO_2 for each electric MWh generated, which represents less than 3% of mineral coal specific emissions. When multiplying this difference for the annual coal-based electricity generation in the Brazilian matrix in 2022, of 15327 GWh [40], it results in avoiding up to 14.0 equivalent Mt CO_2 each year, when converting 50% of the total installed coal-based capacity. Although coal currently represents only 3.3% of Brazilian electricity generation, it is responsible for around 24.4% of CO_2 emissions in that sector. The conversion of 50% of coal-based installed capacity to dry types of biomass would result represent an annual reduction of around 12% in annual CO_2 emissions in the electricity generation sector.

4. Conclusions

Under the global tendency of reducing CO_2 emissions and adhering to net-zero targets, it is expected that large scale coal-based systems will have to be converted to the use of renewable fuels, at least partially. In that decision, long term technical and environmental impacts need to be evaluated. This paper approaches the life cycle assessment of coal and different types of biomass when applied in typical configurations of the main coal-based power plants and cogeneration installed in Brazil.

Empirical correlations found in literature were utilized to calculate the chemical exergy of coal and biomass, reassuring that the resulting exergies for low moisture fuels deviate less from their LHV, which slightly increases the exergy efficiency of the thermal power plants from 38,4% to around 39,0% when comparing dry wood chips to pellets. Nevertheless, under the aspect of life cycle specific energy, biomass pellets result in a 19% higher specific energy consumption compared to dry wood chips, due to the significant thermal energy demand of drying and pelletizing stages. Such distinction between the performance of different types of low moisture biomass may only be detected if the life cycle approach is utilized, since energy efficiency within the power plant cycle may be very similar among them.

The analysis of large scale coal-based plants shows that the conversion to dry types of biomass (up to 15% of moisture content) is viable and demands relatively low intervention in the existing infrastructure for coal, as it has been previously demonstrated mainly in European plants. Particularly in Brazil, this kind of conversion is greatly motivated by the high availability and diversity of biomass residues and land for sustainable plantation. From the perspective of life cycle energy efficiency, the use of residues and less processed types of biomass is highly preferrable over pellets.

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Nomenclature

b specific exergy, kJ/kg
$\dot{B}$ exergy flow, kW
$\dot{F}$ fuel energy flow, kW
h specific enthalpy, kJ/kg
$\dot{m}$ mass flow, kg/s
LHV lower heating value, kJ/kg
$\dot{Q}$ heat rate, kW
s specific entropy, kJ/kg K
T_0 Ambient temperature, K
$\dot{W}$ Net power generated, kW
x Mass fraction

Greek symbols

η efficiency
Δ change

Subscripts and superscripts

b exergetic
bio biomass
C carbon
ash ashes
e energetic
f physical
H_2 hydrogen
H_2O water
N_2 nitrogen
O_2 oxygen
q chemical
mup make-up
S sulphur
u useful
stm steam
w water (moisture)

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