Renewable and Non-Renewable Exergy Cost and Specific CO_2 Emission of Electricity Generation: The Brazilian Case

Daniel Flórez-Orrego[a], Julio A. M. Silva[b], Silvio de Oliveira Jr[c].

Polytechnic School, University of Sao Paulo, Sao Paulo, Brazil, [a]daflorezo@usp.br [CA], [c]soj@usp.br,
Polytechnic School, Federal University of Bahia, Salvador, Brazil, [b]jamsilva08@gmail.com.

Abstract:

The average unit exergy cost and CO_2 emissions of the electricity generated in Brazil are evaluated using the national electricity mix and considering the representative profiles of the electricity generation routes. The Brazilian installed capacity is composed of hydropower plants, natural gas, fuel oil and coal fired thermoelectric plants, biomass cogeneration plants, nuclear plants and wind farms. By using exergoeconomy to distribute exergy costs and CO_2 emissions in multiproduct processes and by weighting the CO_2 emissions and the renewable and non-renewable exergy consumption of each type of plant, it is possible to obtain the average unit exergy costs and specific CO_2 emission for the whole electricity generated. An iterative calculation procedure is used to take into account cyclic interactions of the processed fuels and electricity generated. The renewable and non-renewable exergy costs together with the CO_2 emissions provide a reasonable way to compare the electricity and its final applications with other energy sources.

Keywords:

Renewable, Non-Renewable, Exergy Cost, Brazilian Electricity, CO_2 Emissions.

1. Introduction

When the pervasive nature of electricity is considered, the relevance of the electricity sector comes to be straightforward. As an extremely adaptable 'high-grade' energy source it has become fundamental to almost all aspects of modern life [1]. Electricity can be converted into any type of energy, either mechanical or thermal [2]. Therefore, close to 2050, electricity generation plants shall provide twice or three times the amount of electricity that is generated at present time [3]. Indeed, it is set to increase further, principally due to changes in the transport sector. Projected trends in policy and vehicle production point towards an increase in the proportion of battery and hydrogen-powered vehicles (when hydrogen production via electrolysis of water is attempted), both of which depend on electricity [1]. Nevertheless, electricity is not a primary energy source, and its generation efficiency and its emissions should be borne in mind in the conversion process, so that comparisons with other kind of energy resources could be done. In the case of power plants that still require burning fossil fuels to produce electricity, greenhouse gas emissions (GHG) are inherent to their operation. However, besides to those power plants which directly emit GHG in the process, other technologies usually called as "green" still present CO_2 emissions that, if not produced in the generation of the electricity itself, play a role in the upstream and downstream stages of the process (power plant construction, obtainment of fuel, plant operation, wastes treatment, etc.) [4]. This leads to the idea that there exist no zero pollution technologies at all, as it could be misled regarding to electric vehicles and other electric machines [2, 5, 6]. Hence, it is extremely important to appropriately assess the costs and impacts of the use of the different energy resources in the electricity generation, and identify and pursue the most sustainable energy options in order to maximize the welfare of society, environment and economy.

Some authors have already analyzed the electricity generation for different countries using the Life Cycle Analysis (LCA) method. Santoyo-Castelazo et al [7] carried out a LCA of the electricity generation in Mexico. Unlike Brazil, electricity mix in Mexico is dominated by fossil fuels, which contribute with 79% of the total primary energy; renewable energies contribute 16.2% and the remaining 4.8% is from nuclear power. It was found that 225 TWh of electricity generate about 129 million tons of CO_2 per year, of which the majority (87%) is due to the combustion of fossil fuels. As a conclusion, it was found that reducing the share of heavy fuel oil in the electricity mix would help to reduce the environmental impacts from this sector.

In Japan, Hondo [8] presented an LCA of greenhouse gas emissions of power generation systems. Nine different types of power generation systems were examined: coal-fired, oil-fired, LNG-fired, LNG-combined cycle, nuclear, hydropower, geothermal, wind power and solar-photovoltaic (PV). Lenzen et al [9] studied the Australian life cycle energy balance and greenhouse gas emissions of nuclear and nonnuclear power technologies. The analysis is based on a carbon-intensive electricity mix. The study carried out a detailed review of the past surveys and differentiated both kinds of input sources, thermal and electrical ones.

In Switzerland and West Europe, Dones et al [10] applied the LCA greenhouse gas emissions to current and future energy systems for the generation of electricity and heat. The study found that the trend for modern cogeneration systems points to increasing electricity efficiency with simultaneous preservation of high overall efficiency.

Gagnon et al [11] reviewed the status of the life cycle assessments on the options of electricity generation, including impacts from extraction, processing and transportation of fuels, building of power plants and generation of electricity. GHG emissions, land requirements and energy payback ratio accounting for the different types of recent technologies were analyzed in the study. It was concluded that hydropower, nuclear and wind power have the best performance, although pointing out the high land requirements of the former.

A series of Life Cycle Inventories (LCI) of electricity mixes for selected countries in the world is reviewed in [12]. The inventories are based on data of the Swiss electricity grid and applied to the grid of all countries covered in that study. Environmental impacts based on *Eco-points* indicator are studied together with transmission losses and embodied energy.

One of the limitations inherent to the previous analysis is the problem of energy quality, i.e., electric energy must be compared with thermal energy [13]. In the previous works all the forms of energy are converted into the equivalent primary energy using energy conversion procedures, i.e., electric energy is valuated using the energy conversion efficiency of the power plant from primary energy to electricity. This procedure does not represent an appreciable inconvenience when only one input and one output, such as fuel and electricity, are involved. However, when more than one product is produced in the same plant, as in the case of a biomass-fired power plant, which can simultaneously produce sugar, ethanol and electricity, then energy efficiencies, energy costs, or even mass averaging are not adequate to perform a rational distribution of the costs and CO_2 emissions, according to thermoeconomy theory. Furthermore, statistically it is still considered a representative energy conversion efficiency of 30% when evaluating the equivalent primary energy, even dealing with electricity that could be generated in hydroelectric power plants. Clearly, this is not a reasonable assumption for countries like Brazil, where more than 81% of its electricity mix is based on hydropower.

In spite of the fact that different exergy analysis about electricity generation in nuclear and thermal power plants have been performed, to the authors' knowledge, no work have dealt with electricity mixes analysis by using exergoeconomy to properly split exergy costs and CO_2 emissions among the different products of cogeneration power plants. Simulation software such as *Ecosan* or indicators such as *Ecoindicator 95* and *99*, which are widely used to quantify the environmental impact, perform calculations by using subjective weighting factors. However, by using the exergy concept, any use of special factors is not required [14].

In the present study, exergy is used as a rational base to compare the performance of the electricity generation processes using the different energy sources the Brazilian electricity mix is composed of. In due course, the obtained unit exergy cost can be used to compare the electricity and its final use with other types of fuels either renewable (ethanol, biodiesel) or non-renewable (oil-derived products, natural gas, hydrogen). For example, it will allow making comparisons between the use of electricity and natural gas in furnaces, refrigeration, and other applications such as air conditioning and heating; or between electricity, gasoline, ethanol, diesel and natural gas utilization in the transportation sector, among others. On the other hand, CO_2 emissions are accounted for including not only direct emissions, but also indirect emissions which pertain to the previous stages of fuel processing, such as extraction, transportation or fabrication, as well as construction, operation and decommissioning of the power plant. Moreover, this assessment includes the cyclic influence as a consequence of the utilization of the electricity and processed fuels in the different electricity production routes. For processes in which more than one product is produced, unit exergy costs and CO_2 emissions are distributed using exergoeconomy criteria, which avoids the product and sub-product classification, allocating the costs and CO_2 emissions to all products of a multiproduct plant.

2. Methodology.

The presented approach is based on thermoeconomy methodologies [15-21], also known as exergoeconomy when only exergy costs are involved. Some basic definitions are used in this work: the Non-Renewable Unit Exergy Cost (c_{NR}) is the quantity of non-renewable exergy necessary to produce one unit of exergy of the analysed substance (e.g., water, wind, biomass nuclear or fossil fuel) or electricity in [kJ/kJ]. The Total Unit Exergy Cost (c_T) includes the Renewable (c_R) and Non-Renewable Unit Exergy Costs. Finally, even though the term "fuel" is generally used to designate substances that mainly store chemical exergy, in contrast to those used to produce mechanical exergy from kinetic or potential exergy (such as wind or water in a reservoir), at the present study, the term "fuel" is also used to represent any substance used to produce power. Thus, wind is considered a sort of fuel for wind farms; and, although fission reactions are very different from conventional combustion reactions, nuclear element is regarded as the fuel consumed in pressurized water reactors.

Fuels as present in the environment (petroleum and gas from well, coal and uranium ore, biomass, wind and water) enter the control volume used to analyse each route (B_F^0). Then, for each *processing step i* of a given electricity production route (Fig. 1a), the total and non-renewable exergy costs as well as CO_2 emissions of the processed stream (B_F^i) are accumulated along the route. Extraction, mining, agriculture, transport and fuel production processes are considered as *processing steps* and can be represented as in Fig 1a. Furthermore, since exergy consumption in power plant construction, operation and decommissioning steps can be amortized along the lifetime of the power plant, those steps can also be considered as *processing steps*. Since the exergy consumed in such steps (B_C^i) has been previously processed, it also carries total and non-renewable exergy costs and CO_2 emissions (Fig. 1b). In the case of *electricity generation step* (Fig. 1c), i.e., the power plant itself, the only input into the step is the exergy of the consumed fuel (B_F^n), responsible for the direct CO_2 emissions (M_{CO2}), if the considered fuel contains carbon (Fig. 1d). The desired output is the electricity generated (EE). Considering the exergy flow rate of the fuel fed to the electricity power plant, B_F^n , as the basis to calculate the unit exergy costs and CO_2 emissions of the streams along the different electricity generation routes, one has, $B_F^1 = ... = B_F^i = B_F^{i+1} = \ldots = B_F^n$. In this way, an analysis based on exergy cost balances for each processing and electricity generation step is carried out.

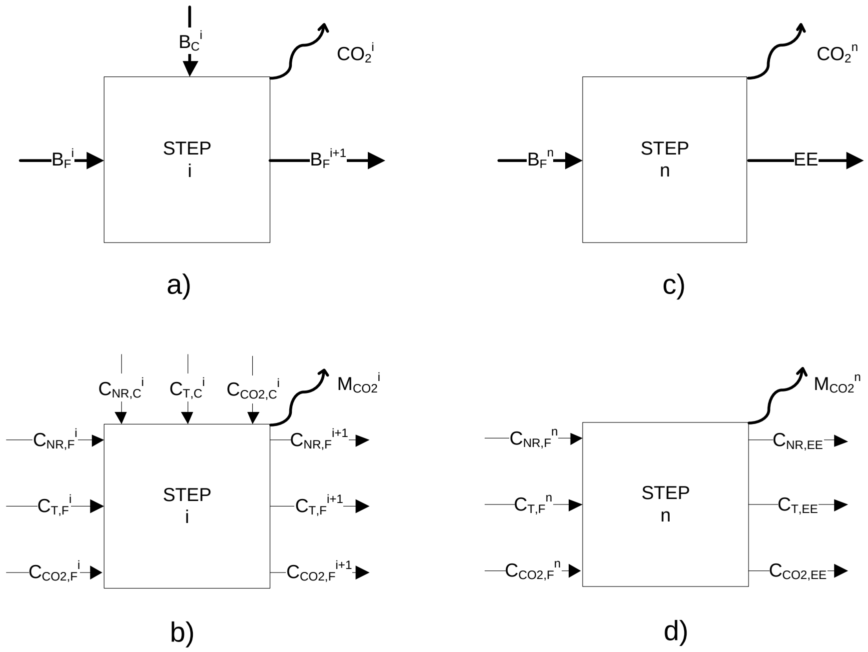

Fig. 1. Exergy consumption and CO_2 emissions steps: (a, b) Processing Step (i), (c, d) Electricity Generation Step (n); $0 \le i < n$.

The mathematical representation of the total and non-renewable exergy cost accumulation along a given *processing step* (see Fig 1b) can be expressed as in Eqs. (1) and (2), respectively, where B stands for exergy rate/flow rate [kW].

$$c_{T,F}^{i+1} B_{T,F}^{i+1} = c_{T,F}^{i} B_{T,F}^{i} + c_{T,C}^{i} B_{T,C}^{i} \tag{1}$$

$$c_{NR,F}^{i+1} B_{T,F}^{i+1} = c_{NR,F}^{i} B_{T,F}^{i} + c_{NR,C}^{i} B_{NR,C}^{i} \tag{2}$$

The CO_2 emission cost (c_{CO2}) is defined as the quantity of CO_2 emitted to obtain one unit of exergy of a given fuel or electricity [gCO_2/kJ]. The direct CO_2 emission in each step is accounted for in the M_{CO2} term [gCO_2/s], analogous to Z term to account for capital investment in thermoeconomy, as shown in Eq. (3):

$$c^{i+1}_{CO_2,F}B^{i+1}_{T,F} = c^{i}_{CO_2,F}B^{i}_{T,F} + c^{i}_{CO_2,C}B^{i}_{T,C} + M^{i}_{CO_2} \quad (3)$$

By dividing both sides of Eqs. (1-3) by the exergy of the fuel processed in the analysed step *i* ($B^i_{F,T}$), and recalling that, $B^1_F = ... = B^i_F = B^{i+1}_F = \ldots = B^n_F$, those equations can be simplified to Eqs. (4-6):

$$c^{i+1}_{T,F} = c^{i}_{T,F} + c^{i}_{T,C} \cdot r^{i}_{T} \quad (4)$$

$$c^{i+1}_{NR,F} = c^{i}_{NR,F} + c^{i}_{NR,C} \cdot r^{i}_{NR} \quad (5)$$

$$c^{i+1}_{CO_2,F} = c^{i}_{CO_2,F} + c^{i}_{CO_2,C} \cdot r^{i}_{T} + m^{i}_{CO_2} \quad (6)$$

where, r^i_T , r^i_{NR} represent the total and non-renewable exergy consumed per unit of exergy of processed fuel [kJ/kJ], respectively, and $m^i_{CO_2}$ is the amount of CO_2 directly emitted in the step *i* per unit of exergy of processed fuel [gCO_2/kJ]. Those terms can be calculated using Eqs. (7-9):

$$r^i_T = \frac{B^i_{T,C}}{B^i_{T,F}} \quad (7) \qquad r^i_{NR} = \frac{B^i_{NR,C}}{B^i_{T,F}} \quad (8) \qquad m^i_{CO_2} = \frac{M^i_{CO_2}}{B^i_{T,F}} \quad (9)$$

Differently from unit exergy cost, for which the initial value entering the control volume of each route is assumed to be equal to the unity, the initial value for CO_2 unit cost is considered null.

Analogously, in the case of the *electricity generation step*, $B^i_{T,C}$ and $B^i_{NR,C}$ are null by definition, so the balance of exergy costs can be written as shown in Eqs. (10-12):

$$c_{T,EE}B_{EE} = c^{n}_{T,F}B^{n}_{T,F} \quad (10)$$

$$c_{NR,EE}B_{EE} = c^{n}_{NR,F}B^{n}_{T,F} \quad (11)$$

$$c_{CO_2,EE}B_{EE} = c^{n}_{CO_2,F}B^{n}_{T,F} + M^{n}_{CO_2} \quad (12)$$

By dividing both sides of Eqs. (10-12) by the electricity generated in the power plant (B_{EE}), Eqs.(13-15) are obtained:

$$c_{T,EE} = c^{n}_{T,F} \cdot r^{n} \quad (13)$$

$$c_{NR,EE} = c^{n}_{NR,F} \cdot r^{n} \quad (14)$$

$$c_{CO_2,EE} = c^{n}_{CO_2,F} \cdot r^{n} + m^{n}_{CO_2} \quad (15)$$

where, r^n represents the total exergy consumed per unit of electricity generated [kJ/kJ] and $m^n_{CO_2}$ is the amount of CO_2 directly emitted in the power plant, per unit of electricity generated [gCO_2/kJ]. Those terms can be calculated by using Eqs. (16) and (17):

$$r^n = \frac{B^n_{T,F}}{B_{EE}} \quad (16) \qquad m^n_{CO_2} = \frac{M^n_{CO_2}}{B_{EE}} \quad (17)$$

By a simple inspection, the values of r^n and $m^n_{CO_2}$ correspond, respectively, to the inverse of the exergy efficiency, $1/\eta_{ex}$, and specific direct CO_2 emissions (if present) of the power plant.

Direct CO_2 emissions, resulting from the burning of any fuel containing carbon, depend on the amount of consumed fuel and its carbon content. Those emissions can be calculated according to Eq. (18):

$$M_{CO_2} = M_C \cdot I \cdot R_m \tag{18}$$

where $R_m = 44/12 \approx 3{,}7$ [kg_{CO_2}/kg_{Carbon}] is the ratio between the molecular weight of carbon dioxide and atomic carbon, M_C [kg_{fuel}/s] is the fuel consumption rate, and I [kg_{Carbon}/kg_{fuel}] is the carbon content of the consumed fuel, based on the elemental analysis.

On the other hand, given that, often in LCA literature, energy consumption in each step *i* of the electricity generation process in a specific route is reported in the way of consumed energy per unit of electricity generated (or *I/O*, input to output ratio, in kJ/kWh or GW/GW_e), it is necessary to calculate the exergy consumed per unit of processed exergy of a given fuel, quantity previously defined as r^i. This is achieved by using the energy efficiency of electricity generation, η_{energy}, and the value of φ, i.e., the ratio between the specific chemical exergy (b^{CH}) and the lower heating value of the fuel (LHV) [22], for both consumed (φ^i_C) and processed (φ^n_F) fuels, according to Eq. (19):

$$r^i = \underbrace{\left(\frac{E^i_C}{E_{EE}}\right)}_{I/O} \cdot \frac{\varphi^i_C}{1} \cdot \underbrace{\left(\frac{E_{EE}}{E^n_F}\right)}_{\eta_{en}} \cdot \frac{1}{\varphi^n_F} \qquad \left[\frac{kJ}{kJ}\right] \tag{19}$$

where E stands for energy rate/flow rate. The value of E^i_C is the energy of the consumed fuel, which can be total or non-renewable; E^n_F is the energy of the processed fuel reaching the power plants ($E^1_F = \ldots = E^i_F = E^{i+1}_F = \ldots = E^n_F$); and finally, E_{EE} is the electricity generated on each route. It must be pointed out that in the case of the exergy associated to substances like water and wind or to electricity, the value of φ is considered equal to unity, that is, the potential and kinetic energy are equal to the potential and kinetic exergy of the substances. In the case of the power plant, the value of r^n can be calculated by using Eq. (20):

$$r^n = \underbrace{\left(\frac{E^n_F}{E_{EE}}\right)}_{1/\eta_{en}} \cdot \varphi^n_F \qquad \left[\frac{kJ}{kJ}\right] \tag{20}$$

On the other hand, direct CO_2 emissions per unit of exergy of processed fuel in the step *i* can be calculated as shown in Eq. (21):

$$m^i_{CO_2} = \underbrace{\left(\frac{E^i_C}{E_{EE}}\right)}_{I/O} \cdot \underbrace{\left(\frac{E_{EE}}{E^n_F}\right)}_{\eta_{energy}} \cdot \underbrace{\left(\frac{M^i_C}{E^i_C}\right)}_{1/LHV^i_C} \cdot I^i_C \cdot R_m \cdot \frac{1}{\varphi^n_F} \cdot 1000 \qquad \left[\frac{gCO_2}{kJ}\right] \tag{21}$$

where I^n_C is the carbon content of the consumed fuel, fed as an input into step *i* in order to process the fuel processed in such step. Analogously, in the case of the power plant, the direct CO_2 emissions per unit of electricity generated can be calculated by using Eq. (22):

$$m_{CO_2}^{n} = \underbrace{\left(\frac{\mathrm{E_F^{\mathit{n}}}}{\mathrm{E_{EE}}}\right)}_{1/\eta_{en}} \cdot \underbrace{\left(\frac{\mathrm{M_C^{\mathit{i}}}}{\mathrm{E_F^{\mathit{n}}}}\right)}_{1/LHV_C^i} \cdot I_F^n \cdot R_m \cdot 1000 \qquad \left[\frac{gCO_2}{kJ}\right] \tag{22}$$

where I_F^n is the carbon content of the processed fuel fed to the power plant.

The method can be easily extended to a case with more than one exergy consumption input (fuel and electricity) in a given processing step by using Eqs. (23-25):

$$c_{T,F}^{i+1} = c_{T,F}^{i} + \sum_j \left(c_{T,C}^{i} \cdot r_T^i\right)_j \tag{23}$$

$$c_{NR,F}^{i+1} = c_{NR,F}^{i} + \sum_j \left(c_{NR,C}^{i} \cdot r_{NR}^i\right)_j \tag{24}$$

$$c_{CO_2,F}^{i+1} = c_{CO_2,F}^{i} + \sum_j \left(c_{CO_2,C}^{i} \cdot r_T^i + m_{CO_2}^i\right)_j \tag{25}$$

Where the subscript *j* represents each one of the exergy consumptions of the processing step *i*.

When more than one product is obtained in the same step, either electricity, sugar and ethanol in polygeneration power plants; fuel oil, diesel oil, and other petroleum derivatives in the refinery, or natural gas and crude oil in an offshore platform, an exergoeconomic analysis of the specific step is employed to properly split the exergy cost and CO_2 costs among all the products in a rational manner. Moreover, since the processed streams leaving some processing steps are consumed in other steps, and some processing steps consume the electricity from the grid, an iterative calculation procedure is employed to solve the set of linear equations used to compute the unit exergy costs and CO_2 costs of the electricity generated.

3. Brazilian Mix Overview.

In Brazil, the total electricity demand in 2011 was approximately 567 TWh including the net imports (near to 35.9 TWh), constituting 18.1% of total energy consumption and approximately 8.0% of national CO_2 emissions [23]. The low values of emissions are owed to a mainly renewable (89%) electricity mix, since imports are essentially renewable [22]. It also leads to a lower amount of energy invested to produce electricity owed to the higher averaged efficiency of hydroelectric generation, if compared with other countries where the electricity generation depends on fossil fuels [23]. In fact, Brazilian electricity generation is 8 to 12 times less CO_2 intensive by MWh generated, if compared with USA and China electricity mix, respectively [22].

However, in spite of the Brazilian electricity mix relies on renewable sources, considering the total energy consumption in the country, almost half of the emissions are due to the transportation sector, which in turn mostly uses fossil fuel sources. In fact, approximately half of the oil-derived products in the Brazilian energy mix are consumed in the transportation sector, which by itself represents one third of the total domestic consumption of energy. Only 0.4% of electrical energy was adopted as a source of locomotion, being the residential and industrial sector which made major use of the electricity [22]. This indicates a potential use of electricity in transportation sector provided that its generation cost is more competitive and has lower environmental impact than the conventional and other alternatives sources.

The Brazilian electricity mix, shown in Fig. 2, is currently dominated by renewable sources, predominantly hydroelectric (81.9%) and biomass cogeneration plants (6.6%), followed by natural gas (4.4%), nuclear (2.7%) and oil products (2.5%), with coal products playing a much smaller role (1.4%). Wind power undergoing recent developments still represents only 0.5% of electricity mix [22]. In 2011, installed capacity reached 117.1GW whereas domestic electricity consumption attained 480.1TWh, with 85% of the electricity being generated by the public service suppliers.

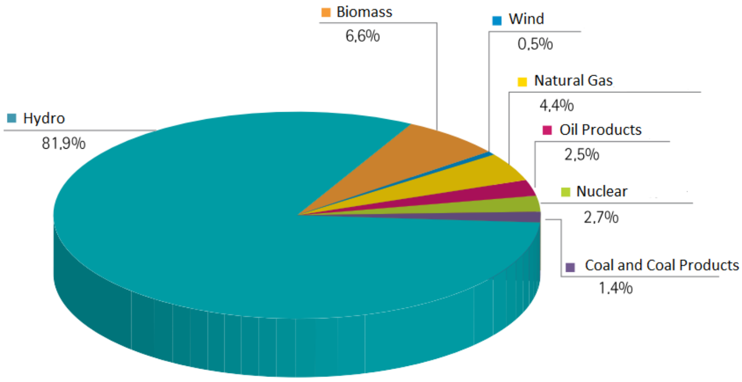

Fig. 2. Domestic electricity supply by source in Brazil [22].

While the electricity generation efficiency and the composition or quality of the fuel are sufficient parameters for the evaluation of the GHG emissions for fossil power plants, the assessment of the entire chain requires other considerations: The differences in the average performances of other facilities in the energy chain, the average lifetime, the origin of the fuel, the fuel transport distances and the means of transport, the efficiency of fuel distribution systems, the environmental standards, the efficiency of infrastructures, the electricity supply mixes involved, and the characteristics of material manufacturing are examples of such considerations [10]. In order to include most of these considerations as well as the effect of the electricity demand in its own generation, then the unit exergy cost and specific CO_2 emissions are calculated according to the integrated Brazilian mix, as shown in Fig. 3. Each route is detailed in section 4, but some considerations are pointed here. Dashed and solid lines correspond to electricity and fuel streams, respectively, showing the interdependence of the Brazilian electricity mix. Petroleum route considers both natural gas and oil-derived fuels production. Furthermore, construction steps are considered only in those routes in which the upstream and downstream energy consumption and GHG emissions play an important role, differently from fossil fuel power plants in which direct GHG emissions accounts for more than 90% of the total emissions. In all the stages in which electricity and processed fuels are consumed, an iterative calculation procedure is considered with exception of the construction step. The reason is that, compared with other steps (agriculture, transport, fuel processing), construction step represents only a small part of the energy consumption and CO_2 emissions of each route. Thus, the omission of such step from the iterative calculation barely influences the results for unit exergy costs and CO_2 emissions and considerably simplifies the analysis and the representation of the electricity grid. For wind and hydro power plants construction step, energy consumption and CO_2 emissions values reported for the Brazilian scenario are assumed [24, 25]. Finally, considering that the fuel conversion and enrichment of nuclear fuel are performed abroad, representative parameters of German and English mixes are considered in order to calculate unit exergy costs and CO_2 emissions for electricity inputs in such steps [26].

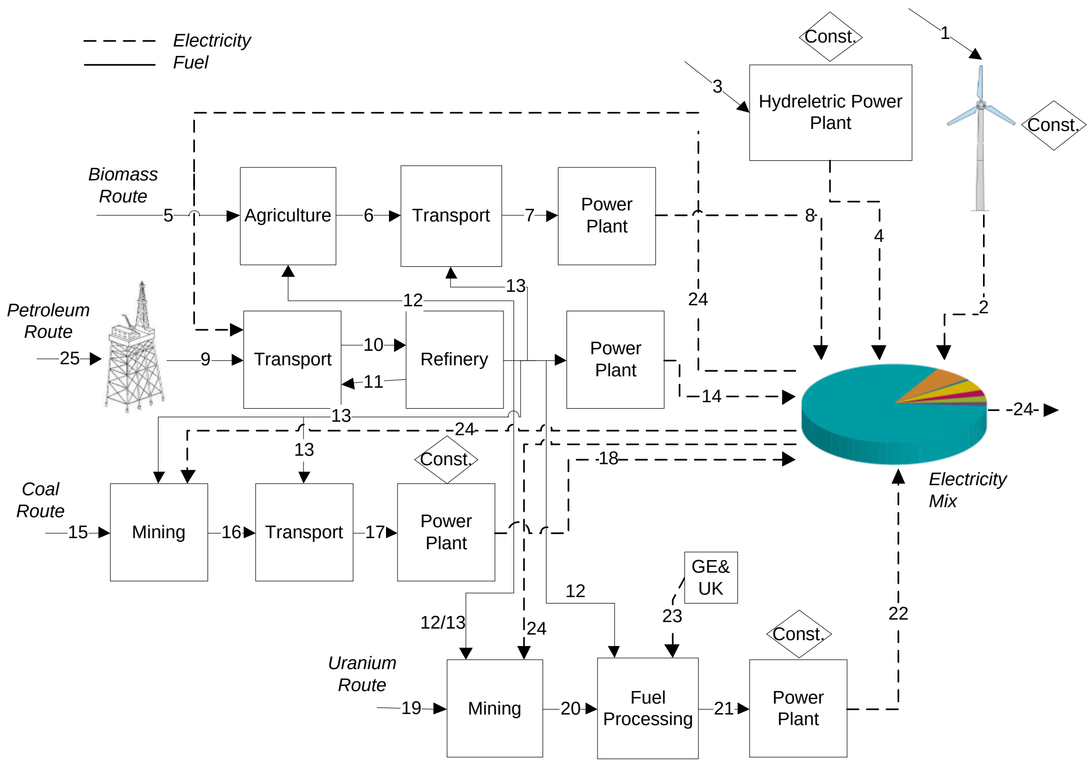

Fig. 3. Brazilian electricity mix. Const: Construction Step; GE&UK: German and English Electricity mixes

Average energy efficiency of power plants that compose the Brazilian electricity mix and the characteristics of their related fuels are shown in Table 1.

Table 1. Characteristics of power plants and fuels considered in the Brazilian electricity mix.

Fuel	Energy Power Plant Efficiency (%)(6)	Lower Heating Value (MJ/kg)	$\varphi = \frac{b^{CH}}{LHV}$ (8)	Fuel Carbon Content - I ($\%C_{mass}$)	Direct Emissions (gCO_2/kJ)
Natural Gas	45.5	47.33	1.032(1)	75.30(1)	0.0565
Oil Products	40.0	41.99	1.066(2)	86.73(2)	0.0710
Nuclear	32.0	4,193,617	0.950(3)	--	--
Coal	35.0	25.44	1.096(4)	59.43(4)	0.0783
Wind	45.0	-	1.000	--	--
Hydro	82.0	-	1.000	--	--
Biomass(5)	15.0(7)	4.44	1.188(5)	22.40(5)	--(9)

(1) Ref. [27, 22], Campos basin natural gas; (2) Ref. [22, 27, 28]; (3) See section 4.2. Nuclear Power route; (4) Ref. [22, 27] , Paraná coal; (5) Ref. [22, 27], Sugar cane biomass; (6) Ref. [9, 22]; (7) Electricity generation efficiency of utilities plant in a cogeneration plant producing sugar, alcohol and electricity; (8) φ is the ratio between the specific chemical exergy b^{CH} and the lower heating value (LHV) of the fuel [29]; (9) Release and capture of carbon are assumed in a closed natural cycle.

4. Electricity generation routes in the Brazilian electricity mix.

As depicted in Fig. 2, Brazilian electricity is generated from different renewable and non-renewable, primary energy sources, most of which have to undergo previous processes before the whole chain of electricity generation is accomplished. In this section each route composing the electricity generation process in Brazil is described, pointing out the nature of the exergy inputs consumed in each step.

4.1. Petroleum route

In order to properly represent the Brazilian scenario, the petroleum route is divided into the following steps:

- Offshore oil and gas production in a Floating Production Storage and Offloading unit (FPSO) is considered. By using the non-renewable unit exergy cost as reported by Nakashima et al. [30] for crude oil and natural gas extraction and primary separation, being 1.006 kJ/kJ and 1.034 kJ/kJ, respectively, and since part of the produced natural gas is consumed in this step, the CO_2 emissions can be easily obtained.
- The oil transportation costs from sea to land are calculated assuming the use of a shuttle tanker Suezmax type. By considering a travelling route of 800 km at a speed of 13 knots and load capacity of 155,000 tons, as well as the offloading operations, it is possible to calculate the exergy consumption supplied by burning bunker fuel and the respective direct CO_2 emissions as 42.32 kJ/(km.t_{Oil}) and 3.06 gCO_2/(km.t_{Oil}). Since bunker fuel is a processed fuel, the determination of its unit exergy costs and CO_2 cost requires iterative calculation.
- The oil transportation from land base to the refinery is performed through pipelines and the national electric grid provides the necessary exergy. By using the Colebrook-White correlation for pressure drop calculation [31], in addition to data of petroleum pipeline and pumping efficiency of 60%, the exergy consumption calculated is 100.3 kJ/(km.t_{Oil}). Since this electricity comes from the national grid, the unit exergy costs and CO_2 emissions of transported oil depend on the whole electricity mix and they are calculated iteratively.
- A fraction of transported natural gas is burnt in gas turbines to drive the compressors that will perform gas transportation through pipelines. Considering a transportation length of 1350 km for Brazil-Bolivia gas pipeline [32] together with an isentropic compression efficiency of 80% and gas turbine efficiency of 37% (LHV basis), it is possible to determine the exergy consumption and CO_2 emissions related to natural gas transportation as 1.063 kJ/km.t_{NG} and 58.2 gCO_2/km.t_{NG}, respectively. Natural gas composition reported by [27] is used to calculate the φ value for natural gas.
- The refining step is based on a typical petroleum refinery as studied by Silva and Oliveira Jr. [33], with a cracking-coking scheme. An exergoeconomy analysis is used to calculate the exergy costs and CO_2 emissions for the different products of the refinery, including diesel and fuel oil used in other routes' steps and for power generation.
- Two different power plants are used for electricity generation step. One of them, with an exergy efficiency of electricity generation of 37.5%, burns fuel oil. The second one, with an exergy efficiency of 44.1% (calculated as an average between a typical gas turbine and a combined cycle efficiency values) burns natural gas.

As long as a very small fraction of the fuels produced in the petroleum route (fuel oil) is used for electricity generation, the contribution of the exergy consumption in construction step (building of platform, pipelines and refinery) to the unit exergy cost and CO_2 emissions of the electricity generated is considered negligible. Instead of that, the exergy consumption and CO_2 emissions of the construction step in the petroleum route are allocated to the unit exergy cost and CO_2 emissions of other fuels produced in the refinery, such as fuels used in transportation sector (gasoline, LPG, diesel oil, and so forth).

4.2. Nuclear Power route

In Brazil, nuclear power generation is carried out by two power plants, Angra I and II, with a total installed capacity of 2000MW and a global capacity factor of 82% [34, 35]. In spite of being called "fuel", the reaction involved in the nuclear fission of uranium is far different from that occurring in a conventional fossil-fired power plant. Therefore, using the efficiency of the power generation (see Table 1), and considering an annual fuel consumption of 47 tons [36, 37], the equivalent lower heating value for the fuel element is determined [9]. Regarding the exergy associated to the energy released in the fission of the fuel, it is calculated assuming an average temperature of fission as T=5000K, which results in Carnot efficiency of 0.95. The aforementioned Carnot efficiency multiplied by the equivalent LHV of uranium approaches the maximum potential work (exergy) that could be obtained in the nuclear reactor, i.e., chemical exergy of the fuel that is used in the power plant. Those results are summarized in Table 1. Some authors [29, 38] suggested that nuclear fuel can be treated as a heat source of infinitely high temperature and, therefore, it could be accepted that the heat transferred inside the nuclear reactor equals the decrease of nuclear exergy and, as a consequence, the exergy and energy efficiencies are basically the same. Obviously, such a temperature is not achieved because of the refrigeration of the fuel elements in the pressurized water reactor (PWR) and exergy efficiency could be lower owed to the irreversibilities presented in the reactor core and water pipeline [29].

Unlike fossil fuel-fired technologies, in nuclear power the majority of the GHG emissions arise from the upstream stages of the fuel cycle [39] and it is highly dependent on the enrichment technology used, diffusion or centrifuge. The older diffusion technology comprises more than half the lifetime total energy consumption. However, centrifuge enrichment technology is as significant as plant construction, operation or decommissioning. The mining and milling of the uranium ore used in Angra nuclear power plants are performed in Brazil (uranium cont. ~ 0.3% wt) and most of the thermal energy used is assumed to come from diesel and natural gas [2, 40], both of which are processed fuels. Meanwhile, uranium conversion to UF_6 and enrichment processes is performed in Europe (Nukem and Urenco companies, respectively). Enrichment process is performed using centrifugal technology by using both electrical and thermal inputs. The electricity consumed in the processes carried out abroad is assumed to be produced in the English and German mixes, considering solely the electricity generation plant, without taking into account the entire generation chain. Thermal input is considered as natural gas [40], with the same exergy costs and CO_2 emissions of Brazilian natural gas. Fuel fabrication is carried out in Brazilian plants by Industrias Nucleares do Brasil (INB). The operation and decommission of the power plant steps are considered as in [9].

4.3. Coal route

The physical and thermodynamic properties of Paraná coal [27] used in this study are shown in Table 1. An average efficiency of 35% for coal-fired power plant is assumed. Although coal fired power plants represent only a small part of Brazilian electricity mix, those technologies are responsible for the highest CO_2 emissions by MWh of electricity generated, making its analysis imperative. Material and fuels inputs for construction, mining, transport and decommission steps are assumed as in [9] whereas for the operation of the power plant, energy consumption is considered as in [4]. Since mining and transportation steps consume diesel oil, the unit exergy costs and CO_2 emissions of the products of each step in coal route are calculated iteratively, according to the integrated Brazilian electricity mix.

4.4. Wind route

Recently, wind farms have been a growing technology in Brazil with an increment of 54% in 2011 [23], reaching a total installed capacity of 1426 MW. However, due to the intermittence of these technologies, only an averaged capacity factor of 25% is achieved. Wind farms have no related fuel or direct emissions, so the ‘fuel’ for wind facilities is ‘free’, but not so the structures and machinery needed to produce wind energy [24]. Indeed, more than 60% of the energy input to a wind power plant comes from the embodied energy of the construction materials and the building and transportation of the towers, along with the required infrastructure (roads, power transmission, etc.). To build a set of wind farms with one gigawatt of installed capacity are required roughly 75,516 tons of steel, 9,049 tons of stainless steel, 305,891 tons of concrete, 211 tons of non-ferrous metals and 19,863 tons of fiberglass [4]. The embodied energy for such materials is reported as 28.34 MJ/kg_{steel}, 51.79 $MJ/kg_{stainless\text{-}steel}$, 1.65$MJ/kg_{concrete}$, 100 MJ/kg_{copper} and 28 $MJ/kg_{fibreglass}$, respectively [41]. Energy storage has not been included in this work. If it were, it would slightly increase the unit exergy cost of the wind electricity [42]. The remaining 30% of the invested energy is involved in the operation, maintenance and decommission of the wind farms. Finally, in this study, the lifetime of the wind farms is considered as 25 years and the power efficiency is assumed as 45%, with the maximum limit (59%) given by the Betz law [43].

4.5. Hydro route

Ribeiro et al [25] carried out a life cycle inventory (LCI) of the Itaipu hydropower plant, the major hydropower plant in Brazil and the second one in the world, responsible for producing 23.8% of Brazilian electricity consumption. The assessment comprises the energy consumption in the construction and operation of the dam and the power plant, the embodied energy of the construction materials (cement, steel, copper, diesel oil, and lubricant oil), gaseous emissions from reservoir flooding and the energy consumption for material and employers transportation. Regarding the primary energy sources used, the authors reported 19.2% corresponds to coal, 15.5% to electricity, 3.6% to natural gas and 61.7% to oil.

Hydropower is considered the lowest emitting technology, although some controversies and uncertainties about the amount of emissions from water reservoir still persist [11, 44]. Dones et al. [45] reported two research studies from Brazil and Canada in which, the influence of the world region (ecosystem) in the intensity of CO_2 emissions when flooding the soil in order to produce electricity, is compared. Canadian research work concluded that reservoirs in tropical regions (where biodegradation is faster) emit approximately 5 to 20 times more GHG than in boreal and temperate regions. Similar results were presented in the Brazilian work, which concluded that using the average capacity factor for seven Brazilian hydroelectric plants, a direct reservoir emission of approximately 340 $gCO_{2\text{-}eq}$ kWh is achieved. This would mean that flooding tropical ecosystems could increase CO_2 emissions related to hydroelectricity generation up to achieve emission levels comparable to those of a gas combined cycle power plant operating with natural gas, and halving the CO_2 emissions of an oil-fired power plant. The determination of such emission levels depend on the decay rates, specific localization and types of cultures, which carries a large amount of uncertainty. Thus, a CO_2 emission intensity of 4.33g/kWh, as reported by Ribeiro et al. [25] is adopted. Furthermore, the efficiency of hydroelectric power stations is high, because losses results only from hydraulic friction in water channels and the passage through turbine blades, as well as from mechanical friction and others irreversibilities in the hydroelectric generator [29]. Typically, the electricity generation efficiency ranges between 70 and 90% for one-fourth of load and full load, respectively.

In this work, a lifetime of 100 years for the dam, with an average conversion efficiency of 82% is considered [35].

4.6. Biomass route

According to ANEEL [46], the capacity of electricity generation from sugar cane bagasse represents 83% of total biomass generation capacity in Brazil and, therefore, this figure is adopted as representative in the present work. For the entire route of sugar cane production and transportation, and combined sugar, ethanol and electricity production, the following assumptions are considered:

- The non-renewable energy consumption for the bioethanol production is reported as $147kJ/MJ_{bioethanol}$, distributed between the consumption of natural gas to produce fertilizers (27%) and diesel consumption in sugar cane transportation and machinery used in agriculture (73%) [47].
- The yield of anhydrous ethanol, reported as 68.3 kg/tc (or 86.3 L/tc) [48], is used to trace back the sugar cane non-renewable energy cost. Together with the exergy and LHV values for natural gas, diesel oil, sugar cane and ethanol, it is possible to calculate the total and non-renewable exergy as well as the CO_2 emission costs of the sugar cane along the agriculture and transportation steps.
- The most common configuration of Brazilian mills is composed of bagasse-fired boilers and backpressure steam turbines operating at 22bar and 332°C [48]. Regarding the cogeneration process in the sugar cane mill, an electricity surplus of 9.2 kWh/tc, as reported by [48] and in agreement with CGEE [47], is considered. Pellegrini and Oliveira Jr. [49] reported the unit exergy cost for sugar, ethanol and electricity generated in a typical sugar cane mill as 1.9 kJ/kJ, 3.38 kJ/kJ and 6.8 kJ/kJ, respectively.

By using this data, the total and non-renewable unit exergy cost and the CO_2 emissions of the electricity generated in sugar cane mills are calculated. The value of the CO_2 emissions agrees with the limits proposed by Weisser [39] for electricity generation technologies using biomass. Since the main goal of sugar cane (biomass) route is to produce sugar and anhydrous ethanol for transportation sector, and only a small fraction of exergy output correspond to electricity, the contribution of the exergy consumption in the construction step to the unit exergy cost and CO_2 emissions of the electricity generated is considered negligible [50, 51].

5. Results and Discussion

In order to compare the intensity of renewable and non-renewable fuels utilization in the highly integrated Brazilian electricity mix, total and non-renewable unit exergy costs and CO_2 emissions of the different streams represented in Fig. 3 are shown in Table 2. These costs are calculated iteratively because of the consumption of the electricity and the processed fuels in their own production. As stated before, the unit exergy cost of primary energy sources that enter the route (streams 1, 3, 5, 15, 19, 25 in Fig. 3) are considered as unity, that is, the uranium and coal ore, petroleum and natural gas from well and biomass are considered as entering at their natural state. Potential and kinetic unit exergy costs of water and wind are also assumed to enter with exergy cost equal to the unity. Meanwhile, CO_2 costs allocated to primary energy sources are considered null. By doing this, the cumulative exergy consumption can be calculated, starting from the fuel obtainment and ending at the electricity production step, comprehending what is often called the *cradle-to-grid* analysis. In Table 2, streams 9a and 9b correspond to crude oil and natural gas produced in offshore platforms, respectively. Stream 10a corresponds to transported crude oil and 10b to transported natural gas, both up to the refinery, whereas stream 14a and 14b are related to the electricity generated in the oil-fired power plant and in the natural gas-fired power plant, respectively.

Table 2. Total and non-renewable unit exergy costs and CO_2 emissions for each stream in the Brazilian mix shown in Fig. 3.

Stream	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9a**	**9b**
c_{NR} (kJ/kJ)	1.0000	0.0308	1.0000	0.0027	0.0000	0.0160	0.0592	0.4022	1.0060	1.0340
c_T (kJ/kJ)	1.0000	2.2553	1.0000	1.2242	1.0000	1.0160	1.0592	7.2025	1.0060	1.0340
c_{CO2} (g/kJ)	0.0000	0.0008	0.0000	0.0012	0.0000	0.0009	0.0039	0.0266	0.0003	0.0019
Stream	**10a**	**10b**	**11**	**12**	**13**	**14a**	**14b**	**15**	**16**	**17**
c_{NR} (kJ/kJ)	1.0075	1.0643	1.0496	1.0643	1.0374	2.7986	2.4178	1.0000	1.0071	1.0078
c_T (kJ/kJ)	1.0082	1.0643	1.0504	1.0643	1.0382	2.8146	2.4296	1.0000	1.0122	1.0129
c_{CO2} (g/kJ)	0.0004	0.0019	0.0027	0.0019	0.0031	0.1998	0.1326	0.0000	0.0005	0.0005
Stream	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**		
c_{NR} (kJ/kJ)	3.1597	1.0000	1.0215	1.0410	3.0905	2.4027	0.3329	1.0000		
c_T (kJ/kJ)	3.1919	1.0000	1.0386	1.0583	3.1420	2.5520	1.7960	1.0000		
c_{CO2} (g/kJ)	0.2479	0.0000	0.0014	0.0026	0.0076	0.1490	0.0172	0.0000		

Meanwhile, unit exergy costs as well as specific CO_2 emissions of electricity generated in each route (streams 2, 4, 8, 14, 18, 22 in Fig. 3) are summarized in Table 3. By using a weighted average based on the generation share, total, renewable and non-renewable unit exergy costs and CO_2 emissions of Brazilian electricity mix can be calculated. These results are graphically represented in Figure 4. Besides, the renewable to non-renewable ratio of the exergy invested in each electricity generation route, which to some extent can be interpreted as a degree of renewability of the process (the intensity of renewable exergy over non-renewable exergy required to produce one unit of electricity) is determined. These results are summarized in the last column of Table 3.

Table 3. Total and non-renewable unit exergy costs and CO_2 emissions for electricity generated in each route shown in Fig. 3.

Power plant	**Share (%)**	**c_{NR} (kJ/kJ$_e$)**	**c_R (kJ/kJ$_e$)**	**c_T (kJ/kJ$_e$)**	**gCO_2/kWh**	**c_R/c_{NR}**
Coal-fired	1.40	3.1597	0.0322	3.1919	892.31	0.01
Oil-fired	2.50	2.7986	0.0160	2.8146	719.16	0.01
Natural gas-fired	4.40	2.4178	0.0118	2.4296	477.22	0.01

Biomass	6.60	0.4022	6.8002	7.2025	95.70	16.91
Nuclear power	2.70	3.0905	0.0515	3.1420	27.42	0.02
Wind farms	0.50	0.0308	2.2245	2.2553	3.00	72.22
Hydro	81.90	0.0027	1.2215	1.2242	4.33	452.41
Brazilian Mix	**(Weighted Average)**	**0.3329**	**1.4631**	**1.7960**	**62.09**	**4.39**

As it can be noticed from Fig. 4, among non-renewable sources, the highest unit exergy costs of electricity generation correspond to nuclear and coal-fired power plants, mainly due to the average low efficiencies considered (35% and 32%, respectively). Furthermore, since uranium conversion and enrichment processes are carried out abroad by using electricity mixes based on fossil fuels, there is an impairing effect on the unit exergy costs and CO_2 emissions of electricity generated on nuclear power plants in Brazil. Besides, it is noteworthy that, for non-renewable exergy sources, the fraction of renewable unit exergy cost is almost negligible and it is evidenced by the renewable to non-renewable unit exergy cost ratio (c_R/c_{NR}~0). This fact shows that, even at fossil fuels production stages, renewable exergy is not widely involved and it sparsely comes from the use of the electricity at the petroleum transportation step and nuclear fuel processing and fabrication. As expected, the highest CO_2 emitting technologies are the coal-fired power plants, followed by the oil-fired ones. CO_2 emissions for natural gas-fired power plants are reduced due to a higher H/C ratio of the fuel and the higher average performance of the combined power plant cycles. Even though fossil-fired power plants present the most marked environmental impacts, it is found that the total unit exergy costs of electricity generated in such facilities are much lower (56-66%) than that presented by sugar cane bagasse-fired power plants in Brazil. The high electricity generation cost in traditional sugar cane bagasse-fired power plants is a consequence of low conversion efficiencies and the large exergy destruction rate at the cogeneration plant in the mills. This shows that, although almost renewable, the typical configurations of sugar cane bagasse-fired power plants are still far from being efficient technologies in Brazil. As demonstrated by Pellegrini and Oliveira Jr. [49], if instead of traditional sugar cane cogeneration plants, more efficient technologies such as Biomass Integrated Gasification Combined Cycles (BIGCC) and Supercritical Steam Cycles (SuSC) were used; lower electricity unit exergy costs could be achieved.

Notwithstanding biomass-fired power plants present the highest unit exergy cost of electricity generation, only 5.6% of such cost is non-renewable. This fact, along with a Brazilian electricity mix dominated by hydropower plants, leads to a low value of the unit exergy costs, CO_2 emission and non-renewable exergy consumption in electricity generation. For the sake of comparison, the European electricity mix emits 462gCO_2/kWh, while the global electricity mix, represented by 84% of the world's electricity production, generates 721gCO_2/kWh [12]. Those values are 7.5 and 11.8 times higher than those values found for the Brazilian electricity mix in this study. Also, owed to the higher efficiency of hydropower plants, which shares the major part of the electricity generation in Brazil, the total unit exergy cost is lower, and thus, exergy efficiency of electricity generation is higher, if compared with countries based on fossil fuels for electricity generation.

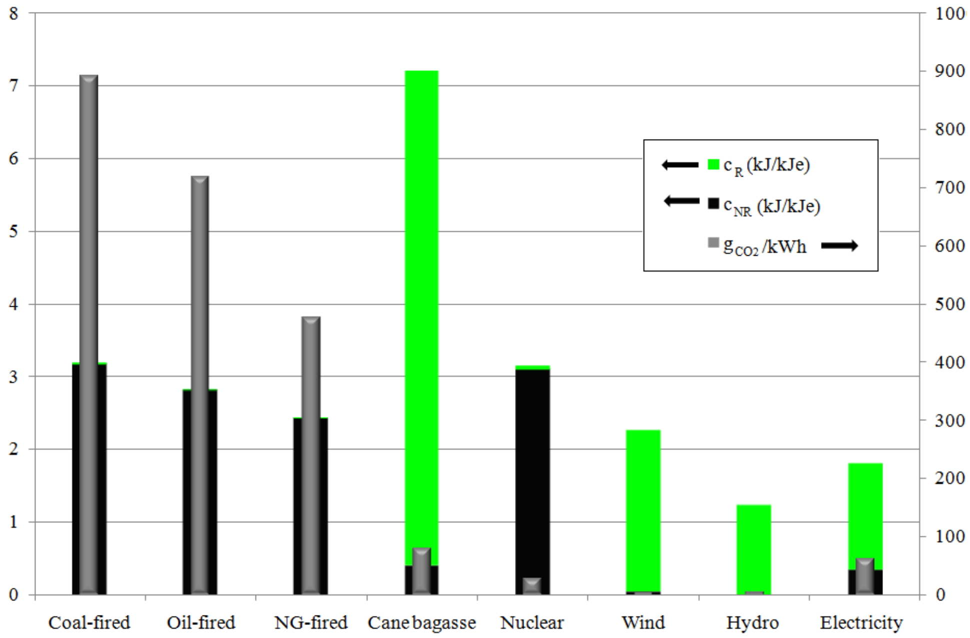

Fig. 4. Unit exergy cost and CO_2 emissions for the different sources of electricity generation.

It is worth of notice that, apparently, total exergy cost of wind and natural-gas fired technologies are almost the same, but contrarily to the wind power plants, total unit exergy costs of NG-fired power plants is practically non-renewable. If energy storage is to be taken into account for intermittent technologies such as wind farms, the total exergy cost could be slightly increased. Furthermore, hydropower plants and wind farms present the lowest specific CO_2 emissions as well as the lowest unit exergy cost; notwithstanding, it is pointed out that controversies related to the flooding dams of vast zones with complex ecosystems should be carefully analysed.

6. Conclusions

An exergoeconomic assessment accounting for the total and non-renewable unit exergy costs and specific CO_2 emissions of Brazilian electricity, based on the national electric mix and the representative profiles of electricity generation routes, is performed. The analysis begins with the fuel obtainment and continues through the different stages of fuel transportation and processing, as well as the construction, operation and decommissioning of the power plant, with electricity generation as the desired output. An iterative calculation procedure is used to determine the unit exergy costs of electricity and processed fuels, since some of those fuels are also used in the Brazilian electricity mix, and, in turn, electricity is employed in the upstream processing stages of the fuels used in the generation thereof. Also, the present approach allows the calculation of direct CO_2 emissions of the power plant as well as the upstream and downstream fuel processing-related indirect emissions, which play a much more important role in technologies different from fossil-fired power plants. Moreover, considering that no previous works have dealt with exergy and exergoeconomic analysis upon electricity mixes, in this work a rational comparison between the utilization of different fuels sources in the electricity generation is achieved. By calculating a weighted average of renewable and non-renewable unit exergy costs of electricity generated in each route, renewable and non-renewable unit exergy costs of 1.4631 kJ/kJ and 0.3329 kJ/kJ, respectively, and CO_2 emissions of 62.09gCO_2/kWh in electricity generation are obtained, leading to a renewable to non-renewable exergy consumption ratio of c_R/c_{NR} = 4.39. Differently from the energy-based surveys, these values can be used to compare the electricity utilization with other kind of exergy sources in a rational manner, whatever substances, exergy fluxes or fuels, such as fossil fuels and biofuels in transportation sector, or natural gas and coal in industrial and residential sectors. Furthermore, it is pointed out that, although biomass-fired power plants present the highest unit exergy cost of electricity generation, only 5.6% of such cost is non-renewable. The high electricity generation cost in traditional sugar cane bagasse-fired power plants is a consequence of low conversion efficiencies. More efficient technologies such as bagasse integrated gasification combined cycles (BIGCC) and supercritical cycles (SuC) should be employed, so that unit exergy costs and CO_2 emissions of biomass-fired technologies could be reduced [49]. On the other hand, the non-renewable exergy cost and CO2 emission contributions of wind and hydropower plants to Brazilian electricity mix are negligible.

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Nomenclature

Latin symbols

c	Unit exergy cost (kJ/kJ)
Const.	Construction Step
B	Exergy rate or flow rate (kW)
b	Specific exergy (kJ/kg)
E	Energy rate or flow rate (kW)
EE	Electricity (kWh) or power (kW)
GE&UK	German and English electricity mixes
I	Fuel carbon content (% weight)
I/O	Input to output energy ratio
m	Specific direct CO_2 emissions (gCO_2/kJ)
M	Direct CO_2 emissions (gCO_2/s)
r	Exergy consumption (kJ/kJ)
R_m	carbon dioxide-to-elemental carbon molecular mass ratio (kg/kg)
T	Temperature, °C, K
tc	Ton of cane

Greek symbols

η	Efficiency
φ	Ratio between chemical exergy (b^{CH}) and lower heating value (LHV)

Subscripts and superscripts

C	Consumed fuel
CH	Chemical exergy

CO_2	Carbon dioxide emission
en	Energy
ex	Exergy
F	Processed fuel
i	i-th step
j	j-th exergy input
n	n-th step
NG	Natural gas
NR	Non-renewable
o	Initial step
R	Renewable
T	Total

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