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Environmental Assessment of the Wind and Solar PV Power Expansion in Brazil From a Life Cycle Perspective

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Abstract: Replacing fossil fuels with renewable energy sources, such as solar photovoltaic (PV) systems and wind turbines, has been a promising pathway not only because of the reduction of greenhouse gas emissions and countries' energy dependence but also thanks to their availability and inexhaustibility. In Brazil, solar PV and wind onshore are key components in the electricity supply expansion. Although the electricity generation from these energy sources could be considered carbon emission-free, they have important environmental impacts outside their operation stage. This paper aims at evaluating of environmental impacts of the Brazilian electricity generation expansion from solar PV and wind onshore through Life Cycle Assessment (LCA). We assess the environmental impacts resulting from the generation of 1 kWh from solar PV systems and wind turbines in a Brazilian context. This analysis is extended to two electricity generation expansion scenarios for these energy sources, established by the Brazilian energy policies. Seven impact categories are analyzed. According to the results, the electricity generation from wind turbines is associated with lower environmental impacts when compared to solar PV systems. Accordingly, the scenario in which the expansion of wind onshore exceeds those of the solar PV is the most environmentally responsible.

Key words: energy planning, renewable energy sources, life cycle assessment, wind onshore, solar photovoltaic

1. Introduction

As the understanding of the socio-environmental consequences associated with the production, conversion, and use of energy expands and deepens, a worldwide transition from fossil fuels to renewable sources of energy becomes increasingly imperative. Accordingly, these low-carbon sources of energy have been an indispensable subject on the international agenda face the increasing global energy demand. They are the fastest-growing energy source in the world and several projections show that they will have a massive contribution in the future [1]. In 2018, electricity generation from renewable energy sources grew 7% when compared to the previous year and around 180 gigawatts (GW) of new renewable power capacity was added [2].

Brazil belongs to the developing countries group that are the leading drivers of the global energy supply expansion. In the last decade alone, the country has experienced an average annual increase of more than 2% in domestic energy supply. A similar evolution is expected for the next ten years [3-5].

Despite a significant share of renewable energy sources, mainly hydroelectricity and biomass, most of the Brazilian energy mix (around 60%) is still represented by non-renewable sources [3, 4, 6]. This current predominance of fossil fuels is associated with challenges related not only to the recognition of degradation and the limits of the natural environment but also to the tackle climate change in line with the Paris Agreement. By contributing to international

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efforts to limit the increase in the global average temperature by 2°C, compared to pre-industrial levels, Brazil has committed itself to reduce its greenhouse gas (GHG) emissions by 37% below 2005 levels in 2025 [7]. However, estimates indicate that the expansion of the national energy supply will increase the annual GHG emissions by 1.9%, totaling approximately 470 Mt of CO_2 at the end of 2026 [3].

Given this scenario, the Brazilian energy policy forecasts an increase in the share of renewable sources in the domestic electricity mix. Today, these sources exceed the 80% mark and will reach 87% by the middle of the next decade [3, 4]. Solar photovoltaic (PV) and wind onshore stand out as the most promising renewable-based sources. They recorded the first and second most installed capacity growth in the period from 2016 to 2017 (3,836% and 21.3%, respectively). It indicates their power installations are multiplying at a blistering pace in the country, and also the need to develop studies focused on their impacts on the socio-environmental dimension, which are still little explored by the Brazilian energy policy [4].

Both wind onshore and solar PV sources are widely distributed and also inexhaustible [2]. Selecting which renewable energy source needs to be prioritized and invested in is complex and inherently a multi-dimensional decision-making process [8].

The present work is part of a comprehensive project concerned with the incorporation of socio-environmental aspects in long-term planning models for the expansion of electricity generation in Brazil. With this in mind, this paper corresponds to its starting point by exploring and evaluating of environmental impacts of the expansion of electricity generation from solar PV and wind onshore energy sources.

For this purpose, we adopt the Life Cycle Assessment (LCA) methodology due to its recognition as the most appropriate current instrument for a holistic environmental assessment over the life cycle of a product or service. This approach proves to be particularly interesting for the case of renewable energy sources, such as wind onshore and solar PV, since most of their environmental impacts are not concentrated in the energy generation stage but distributed throughout their entire production chains.

It is worth mentioning that we do not seek to question the growing interest in these renewable sources, but to highlight their environmental implications in order to anticipate the potential challenges linked to the expansion of electricity generation in Brazil.

2. Material and Methods

2.1 Solar PV and Wind Energy Sources

In a situation in which the expansion of energy demand and the need for decarbonizing of the economy at the global level merge, renewable energy sources emerge as the central pillar of the structure around which the current energy transition is developing [9]. By making use of resources capable of regenerating in the short or medium term, these energy sources prove to be an alternative to fossil fuels, allowing the “neutralization” of GHG emissions during the electricity generation stage. Accordingly, renewable energy sources have been naturally receiving great attention around the world, as well as in Brazil.

Wind turbines convert wind energy into mechanical energy, by using the force of the aerodynamic thrust of the blades, which in turn is transformed into electricity through a generator [10]. Solar PV technology converts sunlight directly into electricity through solar PV cells, which are made up of semiconductors, such as crystalline silicon [11]. The fact behind this “carbon-free” electricity generation is that it is not entirely “clean” [12].

Wind turbines and solar PV systems are associated with several environmental damages or risks [13]. Looking more closely at their upstream supply chains, some of their components and subcomponents are produced from elements known as rare-earth metals. This is the case of the permanent magnets required in some kinds of wind turbines generators and the semiconductor materials used in solar PV cells. These metals demand costly extraction and refining processes, especially from the economic and environmental points of view [12, 14, 15]. When wind turbines and solar PV systems reach their end-of-life, they can either be disposed of in a landfill or recycled to recover valuable materials [12]. Unlike disposal, recycling yields products that can be reused in new wind turbines and solar PV systems or other new products. Despite increasing demand and limit supply, the majority of their wastes are not recycled. In the case of rare-earths employed in all kinds of products, for example, less than 1% of their compound is currently recycled [16].

At the national level, this situation worsens as the Brazilian renewable energy sector has been dependent on imports of components and subcomponents of wind turbines and solar PV systems. This is because the country has not had an industrial and technological park able to produce them cheaper than their imported equivalents, to refine silicon in solar-grade, and to manufacture solar PV cells [17, 18]. China is currently the leading supplier of these material inputs as it has become both the largest wind energy market and also the largest manufacturer and exporter of solar PV cells in the world [17, 19]. When compared to domestic production, importing any consumer goods usually extends supply chains, which in turn involves more financial and environmental costs [20].

These examples above are just a few of many similar examples. They are meant to show us that wind turbines and solar PV systems are associated not only with GHG emissions but also other potential environmental impacts. Capital goods prove to be the main drivers of these problems, and therefore should not be disregarded [12]. Making efforts to mitigate their effects requires, first of all, a comprehensive view of the entire electricity generation chain from systems relying on solar and wind resources. In other words, it means a better understanding of consecutive stages in which several inputs (material, energy, resources), arising from nature or manufacturing processes, are transformed until the decommissioning of wind farms and solar PV power plants, as well as the generation of wastes.

2.2 Life Cycle Assessment (LCA)

LCA makes up the framework of environmental management tools necessary for the current environmental policies and business decisions aimed at environmentally responsible consumption and production [21]. Its approach provides a new lens through which to view and assess the potential environmental impacts of products or services along their entire value chain. Only in this way can we identify and analyze environmental trade-offs that might occur between their different life cycle stages and geographical areas related to their value chains.

LCA is currently standardized by ISO 14040 series for its principles and framework [22] and its requirements and guidelines [23]. An LCA study consists of four steps, namely (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation [22].

In the first step, the goal and scope of the study are clearly defined, including selecting a functional unit and impact categories. In the LCI step, an inventory of relevant energy and material inputs and environmental releases are compiled. In the LCIA step, the potential environmental impacts associated with identified inputs and releases are evaluated. Finally, in the last LCA step, the results are interpreted in order to help decision-makers a more informed decision [24].

In general, this approach has the potential to assist political, technological, and structural decisions more consistently. With regard to the energy sector, it has been used to assess the environmental performance of different technological and energy demand, as well as energy supply options [12].

2.3 Methodology for Assessing Electricity Generation Expansion Scenarios

2.3.1 Goal and Scope Definition

In order to assess and compare the environmental impacts associated with the expansion of centralized electricity generation from wind turbines and solar PV systems in Brazil, the present paper employs a life cycle approach according to the structure and methodological requirements provided by ISO 14040 and 14044 [22, 23]. With this in mind, we carry out firstly a preliminary assessment of their environmental performance associated with 1.0 kWh of electricity produced in a Brazilian context. It provides support for our following analysis focused on the expansion of the electricity supply from these renewable energy technologies in the country.

For this purpose, the system boundaries are defined from the extraction and processing of raw materials to the end-of-life of the power plant. As can be seen in Fig. 1 and Fig. 2, the life cycle of the wind farms and solar PV power plants are divided into six main stages: (i) raw materials processing and components manufacturing, (ii) transportation of imported goods, (iii) components assembly, (iv) power plant installation, (v) power plant operation, (vi) power plant end-of-life. Other transports, connection to the distribution network, transmission lines, and infrastructure processes are not taken into account in our analysis.

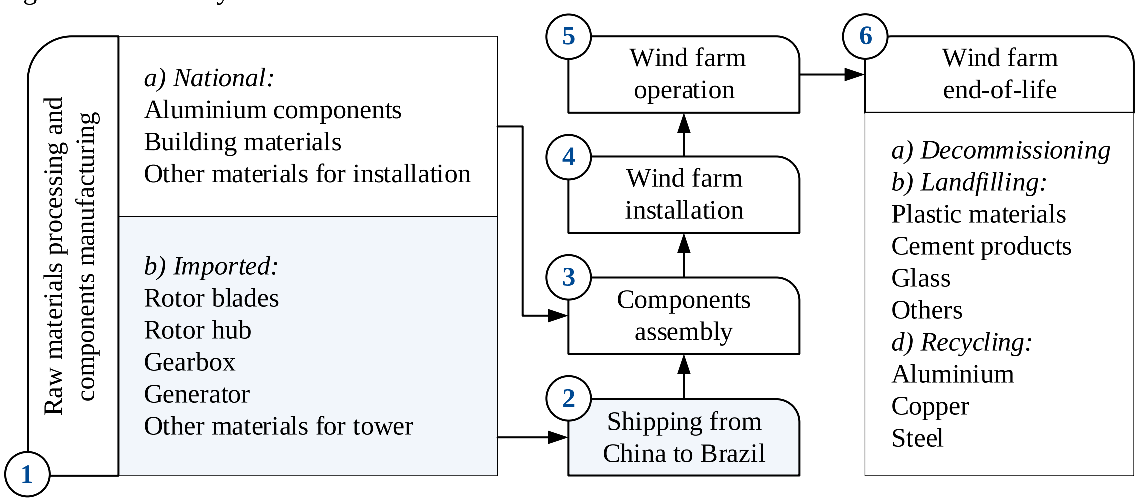

Fig. 1 **System boundary and life cycle stages in the product system of wind turbines.**

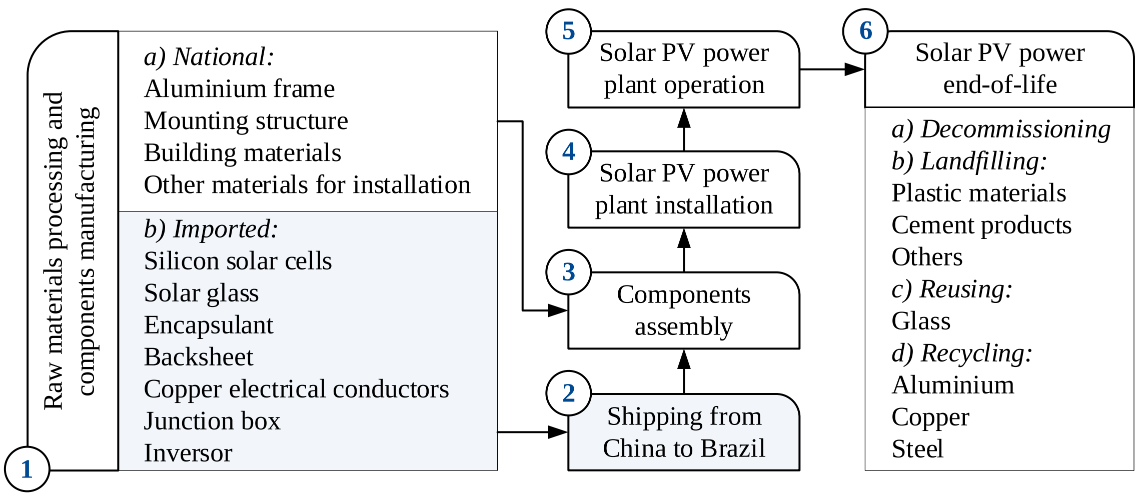

Fig. 2 **System boundary and life cycle stages in the product system of solar PV systems.**

The environmental impact assessment comprises seven impact categories based on the problem-oriented (midpoint) approach of ReCiPe 2016 [25]: global warming potential (GWP), terrestrial ecotoxicity potential (TEP), freshwater ecotoxicity potential (FEP), marine ecotoxicity potential (MEP), land use (LAU), water consumption (WAT), and mineral resources scarcity (MIN). We selected these impact categories based not only on the priority socio-environmental themes for environmental management, outlined in The Ten-Year Energy Expansion Plan 2026 (PDE 2026 as in its Portuguese acronym) [4], but also on the need for material and energy inputs in the manufacturing of wind turbines and solar PV systems components and subcomponents [14, 26]. All the inputs (materials and energy) and outputs (emissions, wastes, and products) were obtained from the Ecoinvent database 3.4 [27] as it is the most comprehensive and transparent international LCI database. It is noteworthy that these data were, as far as possible, modified in order to reflect better the Brazilian context.

This preliminary analysis is extended to two expansion scenarios for wind and solar PV energy sources in electricity generation established by PDE 2026 [4]. The PDE is an annual informative document elaborated by the Energy Research Office (EPE in its Portuguese acronym) under the guidelines and support of the Ministry of Mines and Energy (MME), which aims at indicating the perspectives of the expansion of the energy industry in the horizon up to 2026. The first scenario considered in our analysis (Scenario 1) corresponds to its reference scenario in which the installed capacity of the wind onshore exceeds those of the solar PV energy source. In the second one (Scenario 2), there is an inverse situation due to a 40% reduction in investment costs related to solar PV technology from 2023 [4]. These scenarios are evaluated considering the centralized generation of 1.0 kWh of electricity from both wind turbines and solar PV systems during the period 2020-2026. Table 1 summarizes the information on the scenarios considered. All evaluations were conducted using the SimaPro 8.5.2. The deliverables include (i) LCIA of wind turbines and solar PV systems; and (ii) LCIA of two scenarios of the Brazilian electricity generation expansion.

Table 1 Information on the Brazilian electricity generation expansion scenarios considered.

Energy source	Capacity factor[19]	Installed capacity expansion in 2020-2026 (MW)		Power generation expansion in 2020-2026 (TWh)	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2
Wind	43%	11,824	10,030	1,481	1,274
Solar PV	25%	7,000	10,508	537	705

3. Results and Discussion

3.1 Life Cycle Inventory

Wind turbines are divided into four main components: rotor, nacelle, tower, and foundations (Table 2) [18]. For this system, we make use of the data collected from the Ecoinvent 3.4 database and related to the Brazilian onshore wind farms, whose installed capacity is over 3.0 megawatts (MW)[1], since they represent better the national reality [28, 29]. It assumes that all parts will hold for a lifetime of 20 years and do not have to be replaced.

Table 2 Wind turbines components and their origin.

Wind turbine component	Country source
Rotor	
Rotor blades	Imported (China)
Rotor hub	Imported (China)
Nacelle	
Gearbox	Imported (China)
Generator	Imported (China)
Tower	National
Foundation	National

[1] Electricity production, wind, >3MW turbine, onshore BR.

With regard to the wind turbines' production chain, the raw materials processing and components manufacturing stage corresponds to the industrial processes required not only for the transformation of materials but also for the manufacture of their components. In the importation stage, we consider that materials or components employed in the blade core, rotor hub, gearbox, generator, and special cementitious products are transported from China to Brazil by ocean freight [18, 21]. Thus, rotor blades are manufactured in the national territory from imported material inputs. The wind farm installation stage comprises land use, excavations, construction of roads and foundations, and electricity consumption for the installation of the wind turbines. The wind farm operation stage is associated with the use of lubricating oil for the maintenance of wind turbines, which is carried out once a year. Lastly, the wind farms' end-of-life stage includes the necessary processes for the decommissioning of the entire wind farm and the disposal of its wastes. Regarding the latter one, we consider an end-of-life scenario in which 100% of aluminum, copper, and steel wastes are recycled, while other wastes are sent to controlled landfills [28] (Fig. 1).

Concerning the solar PV power plants, our analysis takes into account solar PV modules made up of polycrystalline (multi-Si) solar panels (since the solar PV market is strongly dominated by technologies based on crystalline silicon and its devices are commonly obtained from multi-Si [11, 30]), as well as inverters, mounting structure, and electrical installation materials, as shown in Table 3. Besides, our model is built using the data of the solar PV power plants, with a capacity of 570 kilowatts-peak (kW_p), a lifetime of 30 years, and global geographical coverage[2], from the Ecoinvent 3.4 database [27, 28].

Similarly to the wind turbines' production chain, the raw materials processing and components manufacturing stage of solar PV systems corresponds

Table 3 Solar PV modules components and their origin.

PV solar module component	Country source
Solar PV panel	
Silicon solar cells	Imported (China)
Aluminum frame	National
Solar glass	Imported (China)
Encapsulant	Imported (China)
Backsheet	Imported (China)
Copper electrical conductors	Imported (China)
Junction box	Imported (China)
Inversor	Imported (China)
Mounting structure	National
Electrical installation materials	National

to the process required for the transformation of materials, and also for the manufacture of their components. When looking at the importation stage, we consider that silicon solar cells, encapsulant, backsheet, copper conductors, junction box, and inverters are also transported from China to Brazil by ocean freight [19, 31]. Then, it is assumed that solar PV modules are assembled in the national territory [19, 32]. The solar PV power plant installation stage encompasses land use, excavations, and electricity and fossil fuel consumption for the installation of the solar PV systems. The operation stage is related to water consumption for cleaning surfaces of solar panels from dust particles and other pollutants [11]. Finally, the end-of-life stage takes into account the required processes for the decommissioning of the entire solar PV power plant and the disposal of its wastes. We consider the same end-of-life scenario adopted in the wind energy option, in which 100% of aluminum, copper, and steel wastes are recycled; while other wastes are sent to controlled landfills [28] (Fig. 2).

3.2 Life Cycle Impact Assessment and Interpretation

3.2.1 Wind Turbines and Solar PV Technologies

As shown in Table 4, it can be seen that the environmental impacts resulting from the electricity generation through wind turbines are concentrated in the raw materials processing and components manufacturing stage. This stage is responsible for 72% of the impacts related to climate change (GWP) and

[2] Electricity production, photovoltaic, 570 kWp open ground installation, multi-Si (adapted in order to represent better the Brazilian context).

accounts for 95% of terrestrial ecotoxicity (TEP), 98% of mineral resource scarcity (MIN), and 77% of water consumption (WAT). At the same time, the end-of-life stage contributes mostly to the marine (MEP) and freshwater ecotoxicity (FEP) impact categories. It is worth noting that the importation stage is responsible for 22% of the total GHG emissions from wind turbines' life cycle. A more detailed examination of the results obtained reveals that it is mainly due to the need to import significant amounts of building materials for reinforced concrete structures. Hence, there is a clear potential for reducing GHG emissions if the possibility of producing in Brazilian territory special cementitious materials required to reinforced concrete structures is considered in the future.

The results for the production of 1 kWh of electricity via solar PV systems are shown in Table 5, broken down into the various impact categories considered in the LCA and at the characterization stage. Likewise, the LCIA results show that the environmental impacts resulting from the electricity generation through PV solar technology are also concentrated in the upstream processes. Indeed, the raw material processing and components manufacturing stage is responsible for 98% of the impacts related to climate change (GWP) and accounts for 99% of terrestrial ecotoxicity (TEP), mineral resource scarcity (MIN), and water consumption (WAT). It is worth to be pointed out that most of these environmental impacts are associated with the manufacture of solar PV systems components as a whole, except for mineral resource scarcity (MIN), which is mainly attributed to the solar PV cells and the mounting structure manufacturing. The solar PV power plant installation stage stands out as responsible for 94% of the impacts related to land use (LAU). Life cycle burdens associated with transportation of the PV systems components from their point of origin to Brazil are almost all below 1%.

Table 4 Results for the production of 1 kWh of electricity from wind turbines (characterization).

Impact category	Unit	Wind turbines' life cycle stages						Total
		Mfg.	Importation	Assembly	Installation	Operation	End-of-life	
GWP	kg $CO_{2eq.}$	1.26×10^{-2}	3.92×10^{-3}	1.26×10^{-5}	5.19×10^{-4}	5.59×10^{-5}	4.80×10^{-4}	1.76×10^{-2}
TEP	kg 1,4-DCB	3.72×10^{-1}	7.99×10^{-3}	1.18×10^{-5}	4.70×10^{-4}	3.61×10^{-5}	1.27×10^{-2}	3.93×10^{-1}
FEP	kg 1,4-DCB	2.88×10^{-3}	2.45×10^{-6}	8.14×10^{-8}	2.80×10^{-6}	2.99×10^{-7}	1.79×10^{-2}	2.08×10^{-2}
MEP	kg 1,4-DCB	4.16×10^{-3}	7.82×10^{-6}	1.19×10^{-7}	4.13×10^{-6}	4.32×10^{-7}	2.13×10^{-2}	2.55×10^{-2}
LAU	m^2 a $crop_{eq.}$	2.37×10^{-4}	1.45×10^{-6}	5.00×10^{-8}	1.81×10^{-4}	2.52×10^{-7}	1.08×10^{-5}	4.30×10^{-4}
MIN	kg $Cu_{eq.}$	4.44×10^{-4}	2.35×10^{-8}	1.01×10^{-9}	3.48×10^{-8}	1.79×10^{-8}	7.79×10^{-6}	4.52×10^{-4}
WAT	m^3	1.65×10^{-4}	5.76×10^{-6}	1.19×10^{-6}	4.01×10^{-5}	3.57×10^{-7}	1.60×10^{-6}	2.14×10^{-4}

Table 5 Results for the production of 1 kWh of electricity from solar PV systems (characterization).

Impact category	Unit	Solar PV systems' life cycle stages						Total
		Mfg.	Importation	Assembly	Installation	Operation	End-of-life	
GWP	kg $CO_{2eq.}$	5.59×10^{-2}	4.98×10^{-4}	2.57×10^{-4}	2.78×10^{-5}	6.65×10^{-9}	6.11×10^{-4}	5.73×10^{-2}
TEP	kg 1,4-DCB	1.17	1.02×10^{-3}	2.06×10^{-4}	2.11×10^{-5}	4.64×10^{-9}	6.47×10^{-3}	1.17
FEP	kg 1,4-DCB	2.98×10^{-3}	3.12×10^{-7}	1.52×10^{-6}	1.98×10^{-8}	3.58×10^{-10}	2.41×10^{-3}	5.40×10^{-3}
MEP	kg 1,4-DCB	4.76×10^{-3}	9.95×10^{-7}	2.21×10^{-6}	3.82×10^{-8}	4.85×10^{-10}	2.89×10^{-3}	7.66×10^{-3}
LAU	m^2 a $crop_{eq.}$	1.03×10^{-3}	1.85×10^{-7}	8.87×10^{-7}	1.58×10^{-2}	1.05×10^{-10}	1.16×10^{-5}	1.69×10^{-2}
MIN	kg $Cu_{eq.}$	5.73×10^{-4}	3.00×10^{-9}	2.17×10^{-8}	3.07×10^{-10}	1.10×10^{-11}	5.00×10^{-6}	5.78×10^{-4}
WAT	m^3	1.69×10^{-3}	7.32×10^{-7}	2.06×10^{-5}	8.12×10^{-8}	1.93×10^{-9}	3.23×10^{-6}	1.71×10^{-3}

In general, these results are consistent with previous studies [12, 33, 34]. Concerning the global warming potential (GWP) impact category, for example, our results corroborate with previous findings that reported that the generation of 1 kWh of electricity is associated with 0-30 $gCO_{2eq.}$ [12], 15 $gCO_{2eq.}$ [33], and 16 $gCO_{2eq.}$ [34] for wind turbines; and 50-75 $gCO_{2eq.}$ [12], 70 $gCO_{2eq.}$ [33], and 50 $gCO_{2eq.}$ [34] for solar PV systems. In the case of wind turbines, this convergence becomes even more apparent when the importation-related GHG emissions are disregarded since these findings were obtained from studies that reflect the Chinese and European contexts, in which there is no need for imported product transportation over long distances like Brazilian context demands. In the case of both renewable energy technologies, the end-of-life stage plays a significant role in freshwater (FEP) and marine ecotoxicity potential (MEP) impact categories, mainly due to the unavoidable generation of wasted and their subsequent and probable disposal [12].

When comparing the environmental performance of their electricity generation chain, we can observe that solar PV system option proves to be more impacting than wind turbines in most of the impact categories considered: global warming potential (GWP), terrestrial ecotoxicity potential (TEP), land use (LAU), mineral resource scarcity (MIN), and water consumption (WAT). On the other hand, wind turbines option dominates the impact categories related to freshwater (FEP) and marine ecotoxicity potential (MEP). To compare the environmental performances of solar PV electricity generation with that of wind on shore, their life cycle impacts are plotted in Fig. 3.

3.2.2 Electricity Generation Expansion Scenarios

When analyzing the environmental performances of the electricity expansion scenarios under the impact categories considered, Fig. 4 shows that Scenario 2 is associated with more significant environmental impacts than Scenario 1 on global warming potential (GWP), terrestrial ecotoxicity potential (TEP), land use (LAU), mineral resources scarcity (MIN), and water consumption (WAT). Considering all impacts have the same environmental relevance, it is possible to conclude that the generation of 1 kWh of electricity from the pair of wind turbines and solar PV modules in Scenario 1, during the period 2020-2026, is more environmentally responsible vis-à-vis Scenario 1. This result can be explained not only by the environmental load from the raw materials processing and components manufacturing stage of solar PV components but also by the lower capacity factor of solar PV power plants, i.e., how often a power plant runs for a specific period of time, when compared to wind farms.

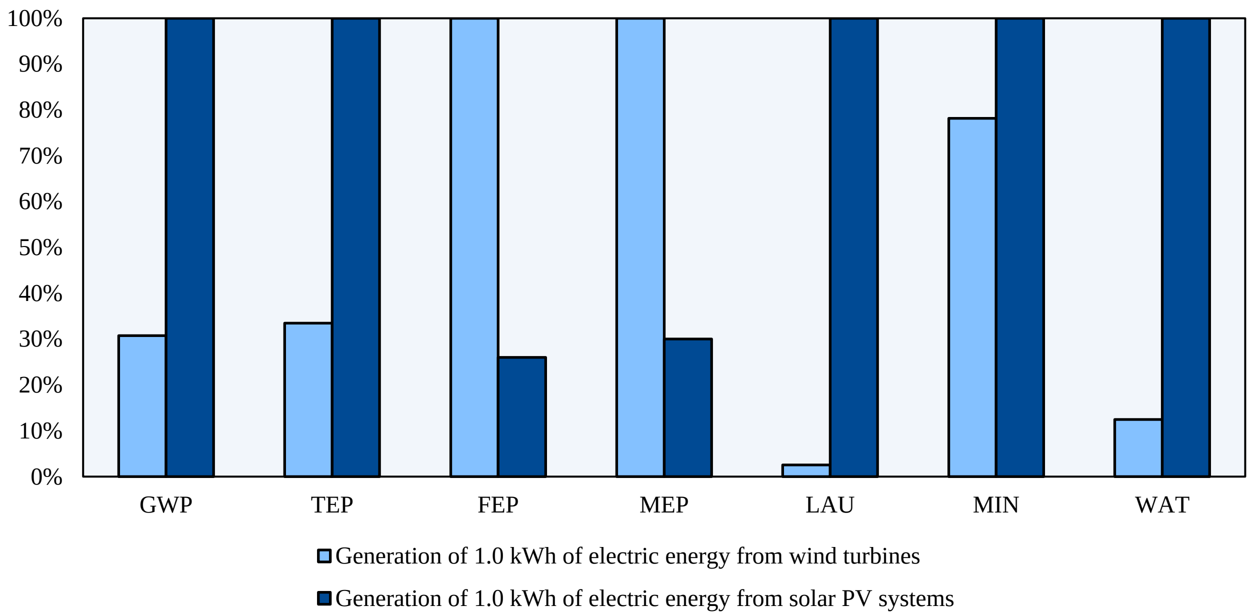

Fig. 3 Results for the production of 1 kWh of electricity from wind turbines and solar PV systems (characterization).

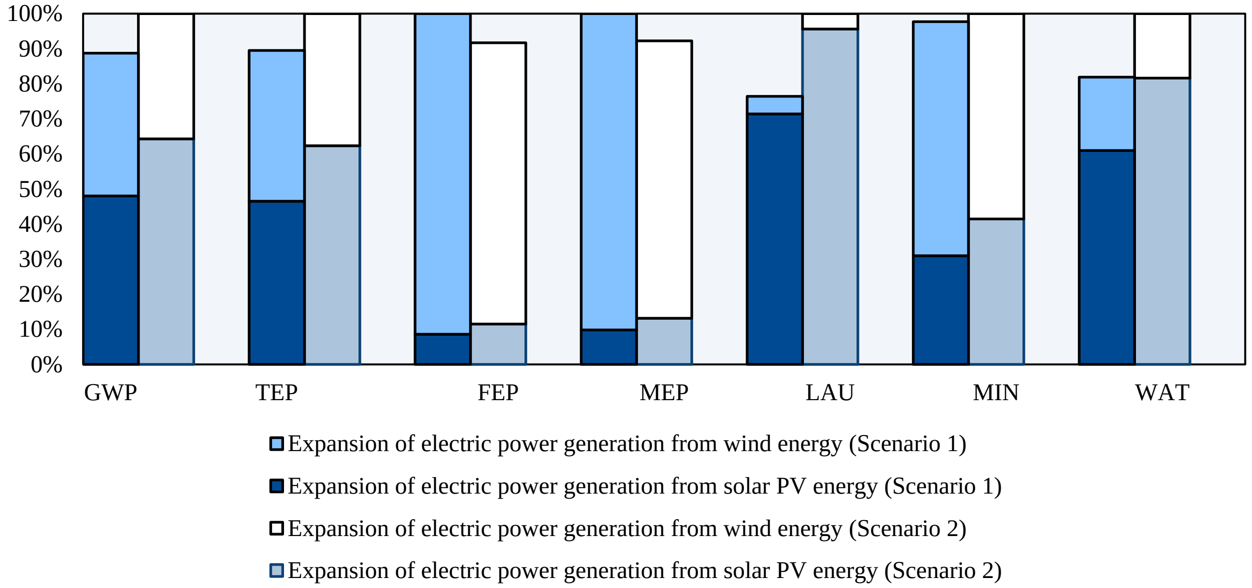

Fig. 4 Results for the production of 1 kWh of electricity from wind turbines and solar PV systems in Scenario 1 and Scenario 2 (characterization).

It must be noted that defining the most appropriated share of wind onshore and solar PV in the Brazilian electricity mix depends, besides the impact categories considered in our analysis, on other factors, such as social, economic, technical, location, public policies, etc.

4. Conclusion

The worldwide economy that is now fuelled largely by non-renewable resources will be powered increasingly by renewable resources. By exploring the environmental performances of the most promising renewable energy sources in the medium-term in Brazil, this paper highlighted the need to shed light on the inevitable but unintended environmental problems of the current energy transition. More specifically, it revealed that the generation of electricity from wind turbines is associated with lower environmental impacts when compared to the same electricity generation from solar PV systems.

Accordingly, the results of the evaluation of electricity generation expansion scenarios indicate Scenario 1 (in which the expansion of the installed capacity of wind source exceeds those of the solar PV energy source) as the most environmentally responsible, when compared to Scenario 2 (in which the expansion of the installed capacity of solar PV exceeds those of the wind energy source).

It is worth pointing out that these results do not represent the most adequate path for the Brazilian electricity mix. Besides environmental aspects, it depends on other factors, such as social, economic, technical, location, public policies, etc. Furthermore, different considerations and system boundaries among various studies of electricity generation from wind turbines and solar PV systems can lead to significant variations in LCA results.

LCA proves to be a useful tool not only for assessing the potential environmental impacts of products or services along their entire value chain but also for supporting policymakers to design future scenarios environmentally responsible.

Finally, since sustainability has become a fundamental value of society, and this concept has been encouraging a global debate about the consideration of socio-environmental issues during the decision-making process in the electricity sector, this work has been being expanded in order to encompass its social and economic dimensions.

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