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Indirect GHG emissions in hydropower plants: a review focused on the uncertainty factors in LCA studies

Emissões indiretas de GEE em usinas hidrelétricas: uma revisão focada nos fatores de incerteza em estudos de ACV

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ABSTRACT: Although Life Cycle Assessment (LCA) is standardized, there is a wide range of approaches and discussions of the methodology evaluating of environmental impacts in different contexts in energy production. This review aims to present some findings, and highlight and discuss factors that influence the Life cycle Assessments (LCAs) of Hydropower Plants (HPPs) such as: indirect emissions; different stages of HPPs (construction, operation and decommissioning), the scale/productivity of HPPs; types of projects (reservoir and run-of-river), and land use. This study presents the comparison of different energy sources through the LCA and the comparison between several HPP with their different characteristics. Most of the results obtained by HPP LCAs indicate that the construction phase is the most influential phase for indirect emissions due to the use of steel and concrete. There is an important relationship between impact and production, since plants with higher productivity will have their impacts diluted during their lifetime. The comparison of the LCA results of HPPs with the LCA of other energy sources indicates that, for the category analyzed (Global Warming Potential-GWP), HPPs have a good environmental performance considering the emissions quantified. The object of this study is indirect emissions and not direct emissions, which are important, but require another approach. This review also indicates some uncertainties related to the LCA of the HPPs and the need to conduct future studies on the environmental impacts of UHEs. We also present suggestions that should contribute to improve the use of the LCA methodology.

Keywords: hydroelectric power plants; life cycle assessment; GHG emissions; energy.

RESUMO: Embora a Avaliação do Ciclo de Vida (ACV) seja padronizada, há uma ampla gama de abordagens e discussões sobre a metodologia referente à avaliação de impactos ambientais em diferentes contextos na produção de energia. Esta revisão tem como objetivo apresentar algumas descobertas, e destacar e discutir os fatores que influenciam as Avaliações do Ciclo de Vida (ACVs) das Usinas Hidrelétricas (UHEs), tais como: emissões indiretas; diferentes fases das UHEs (construção, operação e desativação), relação escala/produtividade das UHEs; os tipos de projetos (reservatório e fio d'água); e o uso da terra. Este estudo apresenta a comparação de diferentes fontes de energia através da ACV e a comparação entre diversas UHE com suas diferentes características. A maioria dos resultados obtidos pelas ACVs de UHE indica que a fase de construção é a mais influente para emissões indiretas devido ao uso de aço e concreto. Existe uma importante relação entre o impacto e a produção, uma vez que plantas com maior produtividade terão seus impactos diluídos durante sua vida útil. A comparação dos resultados de ACV das UHEs com a ACV de outras fontes de energia indica que, para a categoria analisada (Potencial de Aquecimento Global – GWP), as UHEs apresentam um bom desempenho ambiental considerando as emissões quantificadas. O objeto de estudo desta análise são as emissões indiretas e não as emissões diretas, que são importantes, mas demandam outra abordagem. A presente revisão também indica algumas incertezas relacionadas à ACV das UHEs e a necessidade de realizar estudos futuros sobre os impactos ambientais das UHEs. Também apresentamos sugestões que podem contribuir para melhorar o uso da metodologia da ACV.

Palavras-chave: centrais hidrelétricas; avaliação do ciclo de vida; GEE; energias renováveis.

1. Introduction

Economic growth in the current scenario requires greater energy production to meet demand. Producing more energy sustainably and with less environmental impact is a challenge. Renewable energy sources, including hydropower, can meet this demand, especially in countries with high hydroelectric potential, such as Brazil. However, HPP emissions are influenced by several factors, and evaluating the environmental and social impacts caused by this form of generation is a complex task. One of the tools used for these analyses is Life Cycle Assessment (LCA) which is a methodology for environmental damage analysis defined as "the study of environmental aspects and potential impacts throughout a product's life (i.e., cradle-to-grave) from raw material acquisition through production, use and disposal" (ISO, 1997). LCA methodology uses a holistic approach since it identifies the main impacts, and also identifies at what stage improvements can be applied to prevent damage from propagating from one stage to another (Azapagic, 1999).

Although LCA is standardized (ISO, 1997), there are a wide range of approaches and discussions of the methodology regarding the evaluation of environmental impacts in different contexts in the area of energy production. Among these studies are the following: Queiroz *et al*. (2012) carried out the LCA in the process of producing biofuel from a palm tree in the Brazilian Amazon. Matuszewska (2011) identified the configuration of geothermal systems using LCA. García-Valverde *et al.* (2010), Laleman *et al.* (2011), Desideri *et al.* (2012), Frischknecht *et al.* (2015), Schwartfeger & Miller (2015) and Aristizábal *et al.* (2016) applied the LCA to study the environmental damages of photovoltaic systems. Brizmohun *et al.* (2015) carried out the LCA study with the objective of identifying the environmental damage of power generation in Mauritius.

In respect to HPPs the analysis of emissions produced using the LCA methodology is accompanied by many uncertainties and some limitations as in Dones *et al*. (2007) and Turconi *et al*. (2013). Since the characteristics of each plant such as location, size, type, productivity, among others, influence the analysis, requiring that the methodology be well defined and described for each study. Due to the importance of HPPs in the world scenario of energy production, studies using LCA to analyze HPPs are increasing in number however there are still few if we consider HPPs located in the southern hemisphere. Many HPPs are being implemented, especially in China, India, and in northern Brazil, with the objective of increasing renewable energy production and meeting the growth of demand (REN21, 2018). For example, Pang *et al.* (2015) analyzed the environmental impacts of a small HPP in China and made a comparison to similar ones in other countries, and Suwanit & Gheewala (2011) used LCA to assess the environmental impacts of electricity generation from mini-HPPs in Thailand. Vattenfall is the largest energy producer of Nordic countries and performed an LCA of all of the electricity-generating technologies presently with the analysis of 4 HPPs (Vattenfall, 2005). Santoyo-Castelazo *et al.* (2011) analyzed the environmental impacts of HPPs in Mexico and other energy sources that are part of the supply network and presented a comparison between them. Flury & Frischknecht (2012) conducted a study which had the objective of describing the environmental impacts of construction, operation and decommission of HPPs with the main focus on Switzerland, extrapolated to other regions such as Brazil. Hanafi & Riman (2015) evaluated life cycle of a mini HPP in Simalungun – Indonesia and showed that the most evident impacts are carcinogenic, and eco-toxicity in marine and freshwater biota generated from the construction of the mini HPP. Therefore, due to the wide diversity of applications for LCA, as mentioned above, a review comparing different perspectives including factors influencing hydropower emissions at the different stages of the LCA, scale and type of building (either reservoir or run-of-river), and land use, would be a major contribution to the current state-of-the-art, since to the best of our knowledge aspects that are common between multiple HPPs have not yet been discussed in a single analysis.

The present work demonstrates the importance of intensifying the study on the application of LCA for HPPs to analyze indirect emissions, considering their specificities in all stages of the life cycle, addressing factors of uncertainty. Producing energy sustainably is a challenge for developing countries, such as Brazil, and building HPPs in countries with high hydraulic potential may be the best solution to the challenge of large-scale energy production. However, careful studies are needed to ensure production efficiency with the least possible damage to the environment. LCA methodology has been an aid tool for such studies.

2. Method

The method used in this paper included five steps.

Delimitation of the scope of research: The scope of the research is to show how different aspects can influence the results of LCA studies of HPPs and present a comparative study of LCA of HPPs.

Selection of literature: The research was doing between 2016 and 2018. The databases used were the Capes Periodicals Portal and the Scientific Electronic Library Online (Scielo) and followed these criteria – 1st) studies that used LCA to analyze environmental impacts of HPPs and were published between 2000 to 2018; 2st) studies that described the main factors influencing the LCA of HPPs. The search keywords were in the following order of priority: LCA, Hydropower, HPP, GWP, emissions.

Identification of the key factors that influence HPP emissions: The literature cites many factors that influence LCAs of HPPs. In this review, the following factors were considered to be the most cited in the surveys: indirect emissions, type of HPP (reservoir and run-of-river), location and climate, size/productivity, and land use.

Review of LCA of HPPs: Review papers published on LCA of HPPs were selected for comparison of results in different contexts, highlighting analyses of an HPP in Brazil. In this review we highlight the Global Warming Potential- GWP category that according to Acero *et al.* (2015) "expresses the climate changes referent to the global temperature caused by greenhouse gases released by human activity, measured in the reference unit kg of CO_2 equivalent (kg CO_2 eq)". According to Amponsah *et al.* (2014), despite high production of electricity by HPPs in countries as China, Brazil, EUA, Canada and Russia, there are few studies on their emissions through the LCA, justifying the inclusion of revisions made by other authors. In this way, it was possible to present a broader range of results to make comparisons between hydropower and other energy sources (in section 3.1), as well as among HPPs with different characteristics (in section 3.2).

Recognition of uncertainties of LCA of HPPs and identification of challenges for future research: The importance of a review study is to identify points that need more attention and that present themselves as challenges for future research, and several papers cite these challenges. These are presented from the point view of the authors in the conclusion.

3. Comparative analyses of LCA of HPPs

In order to make the best possible comparative analysis between LCAs of HPPs, we first discussed the comparative analysis between HPPs and other energy sources, and to further complement the study an analysis of LCAs limited to HPPs with different characteristics was conducted.

3.1. Hydropower and other energy sources

An aspect that is common to many LCA studies is the comparison between different sources of energy production to analyze the environmental viability and the sustainable feature of each one. In this subsection, we will present some comparisons of LCA of different energy production technologies, based on the literature, comparing these results with those from the Curuá-Una (Brazil) HPP LCA study.

Vattenfall (2012) reports the result of several LCAs of power plants. Vattenfall is the company responsible for the distribution of electricity, heat and gas in some European countries (Sweden, Finland, Denmark, Germany, and the Netherlands). The plants analyzed are hydro, wind, nuclear, and thermal energy generated using biomass and coal. The study divided the process into four stages: production and operation of the fuel for operation of the plant, operation, infrastructure (construction, maintenance and deactivation) and waste. Table 1 presents the main energy production technologies and their respective contributions. According to Kumar *et al.(*2011), Steinhurst *et al.* (2012), Vattenfall (2012), Turconi *et al.* (2013), Brizmohun *et al.* (2015) and other authors, the largest amount of emissions is generated by the coal plant in the operational phase. This reinforces the conclusion of the analyzes that the emissions from the construction phase, that is, indirect emissions, are higher for plants that do not burn fuel, but use renewable resources, such as hydroelectric plants and wind farms. For biomass fuel and coal burning plants, direct emissions are higher in the operational phase (Geller & Meneses, 2016).

Turconi *et al.* (2013) produced a review in the literature in 167 LCA studies of the most diverse energy sources (hard coal, lignite, natural gas, oil, nuclear, biomass, hydropower, solar photovoltaic and wind), and they identified emission data for GHG related to each technology (shown in Table 1) and their relation to environmental impact. With respect to environmental impact, the range of values found for the GHG category indicates that hydropower, nuclear and wind are among the best technologies, producing less GHGs, whereas coal, lignite, natural gas and oil have the largest impact.

Brizmouhun *et al.* (2015) used LCA to account for the emission of GHGs in the Republic of Mauritius energy network, whose main source of energy is fossil fuels. There are only eight HPPs in Mauritius (four of them are reservoir and the other four are run-of-river plants). The researchers suggested that the "greatest impacts are caused by the energy produced by the oil while the hydroelectric energy is the one with the least impact", as shown in Table 1.

Gagnon *et al.* (2002) presented a comparative summary of the environmental impact of various sources of electricity production, based on several LCA studies. One remarkable aspect in this study is the high environmental performance of the run--of-river plants, followed by another group that includes wind, solar photovoltaic (PV), nuclear and HPP with a reservoir.

Feng *et al.* (2014) carried out an LCA study of eight different electricity generation technologies in China. For analysis of coal, nuclear, biomass and wind power, data from plants located in China were used, while for oil, natural gas, hydro, and photovoltaic power the Ecoinvent base processes were used, that accommodates about 4'000 datasets for products, services and processes often used in LCA case studies (Frischknecht *et al.*, 2007). The study shows that CO_2 emissions from fossil fuel-based technologies are much higher than emissions from renewable sources of energy when analyzed over the life cycle (Table 1).

Amponsah et al. (2014) reviewed 79 LCA studies including wind power, wave power, photovoltaic, biomass, hydropower that are considered renewable electricity generation technologies (RETs) and compared these to conventional electricity generation sources such as coal, oil, and lignite (Table 1).

Hondo (2005) presented a model for measuring GHG emissions for nine types of energy production technologies, that are, coal-fired, oil-fired, liquefied natural gas (LNG), LNG-combined cycle, nuclear, hydropower, geothermal, wind power and solar-photovoltaic (PV) (Table 1). The author studied the influence of emerging technologies on life cycle GHG emissions and the impacts of technology improvements in the future and showed a reduction from 29.5 CO_2-eq/MWh to 20.3 CO_2-eq/MWh for wind power and 53.4 CO_2-eq/MWh to 26 CO_2-eq/MWh for PV. The choice of materials with more advanced technology can reduce these factors, such as the type of PV.

Littlefield *et al.* (2013) presented a report on the feasibility analysis of seven types of energy production technologies (natural gas, co-firing of coal and biomass, nuclear fuel, wind, hydropower, geothermal, and solar thermal resources) considering different criteria, among them the environmental profile. The environmental profile uses the LCA methodology to assess resource consumption, emissions to air and water, solid waste and land use from each energy production technology (Table 1).

Results of the studies described above and summarized in Table 1 demonstrate the great diversity of approaches to the LCA methodology when used to analyze the impacts of energy production, a fact that justifies a more detailed discussion.

It is worth noting that, when using the relative functional unit kgCO_2-eq/MWh, the LCA considers the impacts caused in relation to the productivity of the plant, and different energy sources can then be compared. In general, in such comparisons, due their higher productivity HPPs have similar results to other renewable technologies such as solar and wind. We can explain this proof considering that in order to produce electricity from solar PVs plant in the same amount of HPPs, for example, PVs needs

TABLE 1 – Life cycle GHG emissions (kgCO2 eq/MWh) of different technologies.

SOURCE	Coal	Oil	Natural gas	Biomass	Solar PV	Wind	Nuclear	Hydro	OBSERVATION
	(kgCO_2 eq/MWh)								
(Feng *et al.*, 2014)	1230	1213.4	855	97.3	76.3	46.4	17.1	13.2	China (Ecoinvent)
(Vattenfall, 2012)	781			15		15	5	9	Nordic Countries (electricity mix)
(Turconi *et al.*, 2013)	600-1050	530-900	380-1000	8.5-120	13-190	3.0-41	3.0-35	2.0-20	Literature review
(Brizmouhun *et al.*, 2015)	1444	754		29				8.6	Mauritius (electricity mix)
(Amponsah *et al.*, 2014)	888	733	499	14.0-650	9.0-300	8.0-124	24.2	2.0-75	Literature review
(Littlefield *et al.*, 2013)	1118		514			16.9-30.4	39.5	27.7-43.8	Literature review
(Gagnon *et al.*, 2002)	960-1050	778	443	118	13	9	15	2.0-15	Literature review
(Hondo, 2005)	975.2	742.1			53	29.5	24	11.3	Japan
(Raadal *et al.*, 2011)	900-1200	790-900	400-500			4.6-55.4		0.2-152	Literature review

SOURCE: Adapted from Geller & Meneses (2016).

more components such as solar panels, batteries and inverters. These in turn use various inputs such as metals and energy for their manufacture, and so the supply chain and its life cycle grows and contributes to various categories of environmental impact (Desideri *et al.*, 2012).

Table 1 shows that the greatest variation in GHG emission quantification is for HPPs (2.0 -152 kgCO_2-eq / MWh) and biomass (8.5-650 kgCO_2-eq / MWh), a result discussed in Topic 4.5.

3.2. Comparison of LCA results only for HPPs

When comparing LCAs done for different HPPs, in order to obtain better interpretation and analysis, it is very important to consider the objective of each study as this leads to specific results. Some studies consider only the GWP factor (Varun *et al*., 2010; Santoyo-Castelazo *et al.,* 2011; Desideri *et al.,* 2012), whereas others present the total of emission for some factors (Dones *et al*., 2007; Raadal *et al*., 2011). There are studies that review several LCAs done by different authors and compare them, such as the study by Raadal *et al.* (2011) and Turconi *et al.* (2013). In the research of Pang *et al.* (2015) as well in the study of Geller & Meneses (2016), results are discussed in the most representative impact categories for each stage of the LCA. Here we present studies whose authors apply these different forms for LCA of HPPs. The selection of these studies was based on using studies that analyzed only HPPs with LCA methodology, that is, separately from other sources, and that used the functional unit kWh or MWh, and the objective was to focus on the differences in the results for these LCAs.

Varun *et al.* (2010) studied the emissions of 6 HPP located in India, of which three are canal-based projects and three dam-toe projects. The results of this study, in relation to the GHG emission are present in Table 2. Varun *et al.* (2012) presented a list of data for 145 small hydropower (SHP) schemes in India, considering three types of SHP projects: canal based, dam-toe and run-of-river, and the emissions are shown in Table 2. The variation in the emission values found in these studies is due to the different characteristics of the HPPs with respect to their capacity, type of technology, location and size of the head.

Suwanit & Gheewala (2011) studied the impacts caused by five run-of-river mini-HPPs, located in Thailand, with capacities of 5.1 MW, 3 MW, 1.25 MW, 2.25 MW and 1.15 MW respectively. The study considered a lifetime of 50 years and a functional unit of 1 MWh. The results for the impact categories analyzed are represented by the average of the five mini-HPPs in Table 2, and the conclusions recorded by the authors indicate that "the main contributors to the impacts are the materials used in construction such as gravel, sand, cement, steel, iron, copper and the energy used by the equipment".

The work of Raadal *et al.* (2011) compared the emissions of HPPs, based on LCAs of relevant published studies. Among the HPPs there were 28 reservoirs and 11 run-of-river plants (Table 2). For the authors, it is important to include the emissions of flooded area, as they significantly influence environmental impacts, and state that the filling stage of the reservoir contributes most to GHG emissions, surpassing emissions from the plant construction phase emissions of HPP.

Hanafi & Riman (2015) conducted an LCA of a mini HPP in Simalungun – Indonesia. The mini hydropower plant operates all day with two generators in a run-of-river system and has a capacity of 9 MW, 80% of efficiency and productivity of 8 MWh. The period of analysis for the mini HPP was a 50 years lifespan, and the main stages of the mini HPP were established as the pre-construction stage, plant construction, and operation. According the authors "most of the impact originates from the construction of the HPP (Table 2), and that the highest environmental impact category is ecotoxicity and release of carcinogenic materials. This is due to the use of materials such as steel, nickel and concrete for the construction of the rapid pipeline". The authors further prove that GWP has low significance in relation to the categories mentioned above. The total GHG emission for the mini-plant was 1.2 kg CO_2-eq/MWh.

Kumar *et al.* (2011) present a literature review of HPP LCA that displays estimates of GHG emissions. The values reported for GHG emissions are in the range of 4-14 kg CO_2-eq/MWh, but the authors state that "there are reports that this number exceeds 150 kg CO_2-eq/MWh (Table 2), when studies include assessments of GHG emissions from land use change (LUC)". The author points out that LUC emissions can be related to all phases: construction and operation (emissions of methane due vegetation decomposition) and from decommissioning (GHGs released from the large amount of sludge deposited over the life of the plant).

Pascale *et al.* (2011) conducted an LCA of a 3 kW HPP small system located in a rural community in Thailand, to quantify their environmental impacts and compare with larger hydropower by seeking better alternatives for electrification of communities. The study analyzed LCA in its entire cycle using the cradle-to-grave model. According to the researchers the results (Table 2) confirm the trend found in reports in the literature: small HPPs have lower environmental performance, that is, cause greater impact per kWh produced than larger HPPs.

Ribeiro & Silva (2010) conducted an LCA study of the largest HPP in Brazil: the Itaipu HPP, which is located on the border between Brazil and Paraguay and has a capacity of 12.6 GW. The study detailed the inventory of material consumption, energy consumption, atmospheric emissions, and land use, and the results presented in Table 2 relate that this HPP has good environmental performance with respect to emissions of GHG. This is due, according to the authors, to the fact that Itaipu is a large HPP with high productivity.

Gallagher *et al.* (2015) analyzed three run-of--river HPPs with capacities of 650kW, 100kW and 50 kW, located in the United Kingdom (UK), and these plants had 5.43 kg CO_2-eq/MWh, 7.39 kg CO_2-eq/MWh and 8.93 kg CO_2-eq/MWh, respectively (Table 2). The authors discussed the fact that there are few studies of LCA for small (~100-1000 kW) and micro (~10-100kW) HPP emphasizing the importance of this study because hydropower is one of the technologies with significant growth potential in the renewable energy sector, and their emissions must be known.

Kadiyala *et al.* (2016) created an index categorizing HPPs according to capacity (micro, small and large) and type (impoundment, diversion, pumped storage, miscellaneous hydropower works). The mean GHG emission resulting from small HPP dams was higher than large hydropower dams of the same type. The highest average emissions were found for pumped storage (Table 2).

Pant *et al.* (2016) related that run-of-river HPPs emit more GHG the lower their capacity and the higher their head. They analyzed three plants with capacities of 30 MW, 33.33 MW and 51 MW in India with results shown in Table 2. According to the authors "small hydro power plant projects have much smaller environmental footprints compared to traditional reservoir storage hydro power projects".

3.2.1. LCA of HPPs detailed in different phases

Pang *et al.* (2015) did a LCA of a small HPP – Guanyinyan, in northeastern China. The plant has 2 turbines each with a generation capacity of 1.6 MW and with average annual production of 6.28 GWh. The lifetime of the plant was designed to be 30 years with 1 MWh as functional unit. The result of this analysis (Table 3) shows the construction

TABLE 2 – HPP- life Cycle GHG emissions (kg CO2-eq/MWh).

	Total (kg CO_2-eq/MWh)	**Study Site/Type**	**Type**
(Pang *et al*., 2015)	28.4	China	dam-toe-based
(Varun *et al*., 2010)	11.91-35.35	India	canal and dam-toe
(Varun *et al*., 2012)	11.34-74.87	India	canal and dam-toe
(Suwanit & Gheewala, 2011)	17.62	Thailand	run-of-river
(Hanafi & Riman, 2015)	1.2	Indonesia	run-of-river
(Pascale *et al*., 2011)	52.7	China	run-of-river
(Gallagher *et al*., 2015)	5.43-8.93	UK	run-of-river
(Ribeiro & Silva, 2010)	4.33	Brazil	Reservoir
(Pant *et al*., 2016)	14.34-19.12	India	run-of-river
(Kadiyala *et al*., 2016)	21-40.63	Literature review	Reservoir
(Kadiyala *et al*., 2016)	3.0-47	Literature review	run-of-river
(Kadiyala *et al*., 2016)	256.63	Literature review	pumped storage
(Gagnon *et al*., 2002)	2	Literature review	run-of-river
(Gagnon *et al*., 2002)	15	Literature review	Reservoir
(Raadal *et al*., 2011) *	4.0-152	Literature Review	Reservoir
(Raadal *et al*., 2011) **	0.2 - 11.2	Literature Review	Reservoir
(Raadal *et al*., 2011)	4.9	Literature Review	run-of-river
(Kumar *et al*., 2011)	>150.0	Literature Review	Reservoir
(Kumar *et al*., 2011)	4.0-14.0	Literature review	run-of-river

* including gross emissions from flooded land

** excluding emissions from flooded land

SOURCE: Adapted from Geller & Meneses (2016).

phase as being the most responsible for the impacts. The authors also carried out a sensitivity analysis to verify what the impacts would need to be to increase and decrease by 10%, and for this they studied the consumption of material such as steel, cement and electricity. The results showed that the change in cement consumption generates greater changes in results, attaining ±6.8%. One of the conclusions reached was that in order to reduce the level of emissions in relation to the energy generated, it is necessary to optimize structural projects, incorporate the use of new materials and use best construction practices.

Table 3 shows the results of two other hydroelectric LCA analyses where the different phases of the life cycle of a power plant are specified: construction, operation and decommission. Zhou (2011) analyzed emissions from the Nam Theun 2 HPP in Laos, and Geller & Meneses (2016) performed the LCA of the Curuá-Una HPP, located in the Amazon region. Zhou (2011) included the emissions produced by the reservoirs (original flooded biomass) and emphasized that carbon dioxide and methane are the most important emissions in tropical reservoirs. These two gases are produced by the decomposition of biomass, the former through aerobic decomposition while the latter through anaerobic decomposition. At warmer temperatures (tropical reservoirs) methane accounts for 85% of the total emissions (Zhou, 2011).

These three studies are used here because they relate a large range of results that can be attributed to the different ways that LCA methods can be applied. In Pang *et. al.* (2015), the emissions were analyzed considering a lifespan of 30 years for a small HPP (1.6 MW), while Geller &Meneses (2016) analyzed a HPP with a greater capacity (30.3 MW) and used a standard lifespan value for HPPs of 100 years. The differences between the results of these two studies can be attributed to the fact that the greater capacity during a longer lifespan results in higher productivity, and the quantities are diluted due to the production factor. The high value found for the operational phase in Zhou (2011) can be attributed to the inclusion of emissions produced by the decomposition of biomass in the area inundated by the reservoir, a factor that was not considered in the other examples.

Geller & Meneses (2016) study were the Curuá-Una Hydroelectric Power Plant (HPP Curuá-Una) which is located 70 km of the city of Santarém, in the northern region of Brazil, in the Brazilian Amazon. Currently, the plant operates with three turbines (30.3 MW), and is considered a large HPP[1], according to Brazilian standards

TABLE 3 – HPP – Life Cycle GHG emissions (kg CO2-eq/MWh) – Phases.

	Total	**Construction**	**Operation**	**Transportation**	**Maintenance**	**Disposal**
			(kg CO_2-eq/MWh)			
(Pang *et al*., 2015)	28.4	27.3		0.2	0.9	0.0
(Geller & Meneses, 2016)	5.4	4.8	0.11	0.46		0.0
(Zhou, 2011)	78.1	2.0-4.2.0-3.0	70.0-80.0			0.55-0.65

SOURCE: Pang *et al*. (2015), Geller & Meneses (2016), Zhou (2011).

[1] According (Kumar *et al*., 2011) a HPP is classified as small or large according to installed capacity. This classification varies according to the laws of each country. In Brazil, a hydroelectric plant is considered small when it has less than 30 MW of installed capacity.

(National Congress, 1998). The plant was inaugurated on 08/19/1977. The production potential for 100 years considers the actual capacity of the plant with 92.89% efficiency. Real data and Ecoinvent database were used to Curuá-Una LCA. Categories evaluated were: Global Warming Potential (GWP), Acidification Potential (AP), Abiotic Depletion Resources (ADP), Freshwater Aquatic Ecotoxicity Potential (FAETP) and Human Toxicity Potential (HTP), and the four life cycle stages were analyzed, as shown in Table 4. As a result of the analysis, Geller & Meneses (2016), describe "HTP, GWP and FAETP are the most affected categories, and have more emissions during the construction phase. This is because fossil fuel was used for electricity production in this phase, which is a large contributing factor in those impact categories. Note that the construction phase greatly contributes in all impact categories. The analysis also showed that the main contributors to environmental impacts are the steel used for infrastructure and equipment such as turbines and generators and the concrete used in building". The authors also concluded that "it is important to notice that the low results for the operation phase are due to lack of data on the emissions of CH_4 and CO_2 in the flooded area. These emissions should be measured directly in the reservoir, but the methodology used in this LCA study does not include this analysis process".

All results presented confirm the need for specific studies in each context and for each objective, since the characteristics of each plant are different, and the objectives of the studies require adequacy of the LCA methodology. According Geller & Meneses (2016) "a direct comparison between HPPs is difficult and should be made carefully because HPPs are highly site-specific and their environmental impacts are associated with their different characteristics."

4. Discussion

The HPPs LCA studies presented above show the variation of the results and also show how important it is to discuss issues related to specificities of HPPs that affect the study of emissions, and in this section some of these factors will be presented that justify this diversity.

TABLE 4 – Contribution of Curuá-Una life cycle phases to each impact category.

Impact category	Reference unit	Complete life cycle	Construction	Operation	Transportation	Decommission
AP	[kg SO_2-eq]	0.0223	0.0189	0.0009	0.0025	-0.000
GWP 100y	[kg CO_2-eq]	5.4659	4.8922	0.1121	0.4679	−0.0065
ADP	[kg Sb eq]	0.0312	0.0247	0.0033	0.0032	0
FAETP 100y	[kg 1.4-DCB eq]	2.4505	2.2971	0.1169	0.0371	−0.0007
HTP 100y	[kg 1.4-DCB eq]	7.2858	6.4277	0.6267	0.2345	−0.0031

SOURCE: Adapted from Geller & Meneses (2016).

4.1. Direct and indirect emissions of HPPs

Emissions produced by the generation of energy are classified in two ways: indirect and direct (Flury & Frischknecht, 2012). The former are the emissions caused by the construction, implantation and deactivation of the plant, which according to Steinhurst *et al.* (2012) include infrastructure of roads and transmission lines, the work of implantation, manufacture of materials, transport, disposal of material, etc. On the other hand, direct emissions are those resulting from the phase in which the plant is in operation, such as burning fuel used for plant operation, land use/flooded area, goods and services for plant operation, etc.

HPPs produce direct and indirect emissions. Direct emissions are produced right after installing and in the first years of the plant's life (Galy-Lacaux *et al.*, 1999; Tundisi *et al.*, 2003; Fearnside, 2008; Raadal *et al.*, 2011; Flury & Frischknecht, 2012; Steinhurst *et al.*, 2012). The review in the present article is not intended to provide details of these results, because another extensive study is needed to address the influence of these factors on direct emissions.

4.2. Reservoir HPPs and indirect emissions

The largest amount of indirect emissions from reservoir HPPs is present during the construction phase that includes the acquisition of raw material (e. g., concrete, steel, etc.), land use, transportation, energy consumption, and fuel consumption, among others. Geller & Meneses (2016) state that the construction stage at the Curuá-Una HPP was the most critical phase in relation to the indirect emissions caused (view Table 3), due to the inputs for deploying the HPP, which is corroborated by other authors (Dones *et al.*, 2007; Steinhurst *et al.*, 2012; Finkbeiner, 2014; Pang *et al.* (2015), concluded that steel and concrete are the largest contributors among the materials used as inputs due to their production chains.

According to Dones *et al*. (2007)the largest contributor to GHG emissions in the construction stage includes cement production and the use of diesel for electricity. Raadal *et al.* (2011) complement that "the major contributing factor related to the infrastructure for the emission of GHGs is the production of concrete and the transport of stones for the construction of dams and tunnels".

Indirect emissions in the construction phase may represent more than 90% in renewable plants (Steinhurst *et al.*, 2012). Vattenfall (2012) reinforce that these emissions dominate the environmental impacts of those plants that do not burn fuel but use renewable resources such as hydroelectric, solar and wind power plants.

4.3. Scale/capacity of the hydropower plants

Regarding the capacity and scale of projects, several authors e.g., Dones *et al.* (2007), Ribeiro & Silva (2010), Pascale *et al.* (2011) and Pang *et al.* (2015) state that larger systems have better environmental performance than smaller systems, due the ratio between the emission rate and the energy produced in MWh in the plant's lifetime. Zhang *et al*. (2007) carried out LCA of two HPPs in China, with 44MW and 3,600 MW, and the GHG emissions were 44 and 6 kg CO_2-eq/MWh, respectively. When using the impact ratio per MWh, a plant that produces more and with a longer life will have its impacts diluted throughout its lifetime, becoming an environmentally viable option to meet larger demands. However, in some circumstances, a small HPP will still be the best option in relation to fossil fuel plants, for example, to serve small populations, to serve rural communities located great distances from the main HPP or as load complement for a given system. LCAs of HPPs with different capacity must be done with caution even when results are parameterized, because the productivity of the plant is not the only factor that influences the environmental impacts.

4.4. Others important factors that influence the emissions of HPPs

Gagnon & Vate (1997) discussed the environmental damage of the complete life cycle of reservoir plants and run-of-river plants, and the former obtained an average of 15 kg of CO2-eq / MWh and the last of 2 kg of CO2-eq / MWh. In these cases, one of the most important emissions factors is the quantity of materials (steel and concrete) for the former that is much higher than that for the run-of-river plants.

A common observation in studies of HPPs is that run-of-river plants have better environmental performance per MWh in the category GWP. However, this comparison does not consider two important issues: the reliability of electricity supply and the other uses of hydropower reservoirs, such as irrigation, flood control, drinking water storage and industrial demands. According Gagnon *et al.* (2002) reliability is only possible when the system can store the water to generate electricity, as in the case of the reservoir HPPs. We should also consider that energy produced by intermittent systems (e.g., wind, solar PV) is generally complemented by other sources and this can greatly increase the emissions of the system.

Currently, large reservoirs are planned and built with additional functions such as irrigation, water flow control, fish farming, etc. In China, the Three Gorges HPP, uses the stored water to irrigate, to facilitate navigation, and control water flow to make it available during periods of drought (Feng *et al.*, 2014; Kumar *et al.*, 2011). In India, many dams are built mainly for water management while hydropower generation is considered as a side benefit. The study of LCA in these cases becomes difficult, because the reservoir's importance as an energy producer is not totally known (Gagnon & Vate, 1997).

A highly discussed issue with respect to LCA of HPPs is to land use change (LUC). Land use of HPPs implies land transformation (flood area and implantation) and occupation (entire occupied area concerning the time of use). According Flury & Frischknecht (2012) most of the land transformation in hydroelectric reservoirs is due to the flooded area and only 1% is due to infrastructure. Fthenakis & Kim (2009) affirm that the longer time a certain area is used for generation of renewable energy the lower is the occupation factor. On the other hand, the amount of energy produced by non-renewable sources (biomass, natural gas, coal, etc.) grows the larger the area occupied.

Land use, such as occupation or transformation, must be critically analyzed when dealing with HPPs. Fearnside (2015) studied the Balbina HPP located in northern Brazil. He points out that this plant may have higher emissions than a fossil fuel plant because the proportion of the size of the reservoir in relation to the energy generated is very high.

Geller & Meneses (2016) show that the occupation of the land at the Curuá-Una HPP in the Amazon region accounted for 1.33E-02 km^2.y/MWh. Considering that 92.89% of the efficiency of its projected production is 29,976,720 MWh in 100 years, if the operation time were reduced to 50 years with the same efficiency, the HPP would produce half this energy, thus increasing the occupation factor and environmental damage.

An important factor to be included in the LCA is the type of technology used and the location of equipment manufacturing (Amponsah *et al.*, 2014). In the particular case of Brazil, the LCA of a HPP must include transport, since most of the equipment is manufactured far from the plant site and often requires more than one type of transport, such as was the case for the Curuá-Una HPP, for which equipment such as turbines and generators were transported by road and by rivers (Geller & Meneses, 2016).

4.5. LCA of HPPs uncertainties and future challenges

The uncertainties related to the results of LCA of HPPs can be attributed to the lack of a standardized method to apply this technique. The use of just one functional unit to conduct comparisons is not enough to guarantee a correct analysis of the results since the definition of the limits or boundaries of the system analyzed vary between studies. Take, for example, LCA for HPP that have a reservoir, where most of the analysis includes all phases (construction, operation/maintenance, and decommissioning), but few studies take into account the emissions of methane and carbon dioxide that occur during the reservoir filling or from the flooded area during the operational phase, as discussed by Fearnside (2008). There are many factors that can influence these measurements, such as pre-existing vegetation, location and climate, and size and depth of the reservoir, as previously discussed. According to Littlefield *et al.* (2013), the renewable energy technologies have the greatest range of uncertainty in GHG results. Gagnon *et al.* (2002) state that uncertainty is greater for biomass and hydropower technologies, as can be seen in Tables 1 and 3. The authors also make evident that emissions from reservoirs in tropical regions can be subjected to large rates of variation due to high temperatures that accelerate the decomposition of biomass.

The search for standards that are specific to the application of LCA method to hydroelectric dams is among the challenges for research in this area. In order to facilitate this process we recommended that (i) a framework be devised in order to evaluate uncertainties, (ii) a standard be defined in order to classify hydroelectric dams with respect to size, geographic location, and climate, (iii) the method of data collection be standardized in order to inventory resources and materials that can be considered as being essential to a LCA of a hydroelectric dam, (iv) and we suggested that a common vocabulary be constructed so that professionals from different areas can contribute to this methodology.

As a challenge for future research related to emissions from hydroelectric dams, several points discussed in this paper highlight the necessity to quantify the emissions from HPPs during their entire life cycle, including emissions produced by the reservoir, and analyze potential emissions from large hydroelectric dams being constructed in China and Brazil. Additionally, the possibilities for integration and optimization of different technologies in order to meet the growing demand for energy generated within the parameters of sustainability should be investigated, along with the development of technologies that produce lower impact in the construction phase of hydroelectric dams.

It is currently understood that the integration of different technologies in the production of energy is a viable alternative for meeting the growing demand for energy in the current economic scenario, and hydropower has an important role in this context. However, there is considerable controversy surrounding the development of hydroelectric dams. Some research studies cite hydropower as being renewable and clean energy source, while others state that their emissions can sometimes be even greater than those from fossil fuels. It is important that this topic be discussed in a context based on results from peer-reviewed scientific studies, and such a scientifically-based discussion will allow for the rigorous evaluation of the most viable forms of production of energy that support the principles of sustainability.

5. *Final considerations*

The present article is a review of LCA of HPPs and compiles aspects that may influence these analyses. The main contribution of this paper is with respect to the specificities related to indirect emissions from HPPs, with emphasis on some special features of reservoir HPPs. Indirect emissions are addressed due to the importance shown by the studies of LCA of HPPs in their construction phase. Different from the direct emissions that are typical of the plants' production stage.

A general trend of results from current research is that HPPs produce lower emissions per generated energy than technologies that use fossil fuels, considering the entire life cycle of the plants. To evaluate the results among the renewable ones such as wind, solar and hydroelectric, the intermittence of the sources must be considered, and in this way, the results can still be favorable the hydroelectric plants. In relation to the phases analyzed by the LCA of the HPPs, most studies state that the construction phase is the one that produces the most emissions with respect to renewable plants. But some studies also cite the emissions from the flooded area and the submersed vegetation as being an important emission factor.

The results obtained by the surveys exemplified here corroborate that LCA can be widely used for the environmental analysis of electricity production systems. However, due to the many factors that influence the analyzes, as shown in the text, more studies are needed to consolidate the methodology to increase knowledge necessary and produce results that are increasingly precise in relation to the LCA of HPPs, thus collaborating in the decision process involving HPPs.

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