Accounting for GHG net reservoir emissions of Hydropower in Ecuador

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Abstract

Hydropower is one of most important considered renewable technologies to provide electricity generation worldwide. Bearing in mind the lack of LCA studies and the development of several hydroelectric projects in Ecuador, the purpose of this paper is to present a complete environmental performance of two hydropower schemes (dam and run-of-river) located in this country, through the life cycle assessment combined with reservoir GHG emissions approach. The run-of-river scheme had better environmental performance than the dam scheme. Very high emissions were found, being 547 Kg $CO_{2\text{-}eq}$/MWh for dam scheme, which most of those emissions were originated in the reservoir, while the run-of-river scheme only score 2.6 Kg $CO_{2\text{-}eq}$/MWh. However, comparing with fossil fuel power plants, hydropower dam case still has lower emissions in its entire life cycle. The paper remark that the majority of LCA studies which focus on dam hydropower scheme only consider the emissions of the construction, putting aside the loss of the ecosystem and the emissions caused by the impoundment. Moreover, the analysis also included the impact associated to water uses since reservoirs are usually devoted to several purposes (flood lamination, irrigation, ecological flow, power generation).

Keywords: *Hydropower-Life cycle assessment-Renewable Energy-Greenhouse gases-Reservoir-Ecuador*

1. Introduction

There is a clear trend worldwide to replace energy technologies based on fossil fuels with technologies based on renewable resources. Hydropower, which is considered a *clean power generation technology*, highlights among renewable energy technologies which in 2013 generated 16.3% of world electricity and 75.1% of total renewable electricity [**1**]. In 2014 and 2015, 37.7 and 33.7 GW of hydropower capacity was put into operation respectively, resulting an estimated world installed capacity of 1212 GW, which confirms and maintains its tendency to grow [**2**] [**3**]. In 2015, 3.8 GW of hydropower were developed in South America [**3**]. Brazil and Colombia have the highest hydroelectric development, having a joint installed capacity over 100 GW which represents the 24% of the technical exploitable potential in the region.

In this context, since 2008 Ecuador is developing several hydropower projects with the aim to have 100% renewable electricity generation in the near future. Until 2012, 44% of its electricity generation came from non-renewable resources like oil and natural gas. Furthermore, about 1% of the energy consumption was imported from Colombia and Peru [**4**]. Currently, it has been estimated that the country has a total hydro energy potential of 74000 MW being only 21500 MW the technically and economically feasible to exploit [**5**]. Ecuador exploited less than 12% of this potential before 2012. The current hydropower capacity has reached 3653 MW [**6**].

Despite of its great advantages as zero direct emissions during its operation, the hydroelectric development may generate considerable environmental impacts which cannot be ignored [**7**]. Life Cycle Assessment (LCA) is an international accepted tool which allows identifying the potential environmental impacts associated with a product or service, throughout its entire lifespan, in other words, from the cradle to the grave [**8**] [**9**]. In these terms, electricity generation systems have been widely assessed, specially hydropower plants, from few kW to over 5000 MW and all its typologies, focusing on either their GHG emissions, energy intensity, carbon or water footprint, through their lifespan [**10**] [**11**]. According to the reviewed literature, the majority of the cases of LCA have been done in Asia [**12**], following by a few ones in Europe [**13**] [**14**], while there is not a reported LCA study from South America except for a life cycle inventory of a Brazilian hydropower plant [**15**]. Moreover, 42% of the LCA studies focus on run-of-river schemes while 45% focus on dam scheme. In terms of greenhouse gases (GHG) emissions, the LCA results may vary widely. For instance, a 9 MW run-of-river located in Indonesia obtained 1.2 Kg $CO_{2\text{-}eq}$/MWh [**16**] while the same hydropower scheme located in Thailand having only 3 kW obtained 52.7 Kg $CO_{2\text{-}eq}$/MWh [**17**]. Some of the GHG emissions ranges reported for these hydropower schemes are 2-5 Kg $CO_{2\text{-}eq}$/MWh [**18**], 2.2-74.8 Kg $CO_{2\text{-}eq}$/MWh [**19**] and 18-75 Kg $CO_{2\text{-}eq}$/MWh [**20**]. Considering hydropower dam schemes, a carbon footprint assessment was carried out in China to compare the emissions from alternative dam construction. It was demonstrated that hydropower with concrete gravity dam have higher emissions than with earth-core rock-fill dam, due to the concrete which has high energy intensity. For the studied cases, their emissions were 11.11 Kg $CO_{2\text{-}eq}$/MWh and 8.36 Kg $CO_{2\text{-}eq}$/MWh respectively [**10**], falling within the reported ranges of 2-48 Kg $CO_{2\text{-}eq}$/MWh and 11-20 Kg $CO_{2\text{-}eq}$/MWh [**21**] [**18**] for those hydropower schemes. Both for dam and for run-of-river small hydropower schemes (< 50MW), their LCA greenhouse gases increase as they increase the drop height and decrease the installed capacity [**22**].

Other authors have analyzed and compared hydropower plants with the main electricity generation technologies, including those ones based on fossil fuels, showing that hydropower has a good environmental performance, particularly with the emissions of GHG in its entire life cycle [**23**] [**7**]. However, it is known that the reservoir of hydropower plants emit a considerable quantity of greenhouse gases which could exceed the emissions of fossil fuel electric generation technologies [**24**] [**25**].

This paper presents, on the one hand, a complete LCA of a reservoir and a run-of-river hydropower schemes developed in Ecuador, and on the other hand, the net GHG emissions of hydropower reservoir caused by impoundment in the first case. The aim is to integrate both approaches to explore the environmental performance of one of the most common electricity generation in Ecuador which it is planned to cover 90% of electricity demand in the near future. The two selected cases were assessed and compared, thus allowing to know how suitable and feasible is to keep promoting this hydropower projects as sustainable ones. Section 2 details case studies, methodology, life cycle inventory and reservoir emissions. The results are presented in Section 3, followed by a sensitive analysis in Section 4. Discussion and conclusions are found in Section 5 and 6 respectively.

2. Materials and Methods

2.1. Case studies and description

The two selected cases were dam and run-of-river scheme respectively. The selection of the hydropower plants was based on typology, geolocation as well as drop height, technology, the installed power and electric generation. It was also considered the availability of the information. Due to Ecuador is crossed by the Andes Mountain, there are two very well identified hydrographic slopes, the Pacific and the Amazon, and in order to have a better contrast and comparison, one hydropower of each area was selected.

First case is Mazar-Dudas, which is a run-of-river hydropower plant scheme, the only one of its kind so far in Ecuador [**26**]. It is a set of 3 consecutive hydropower exploitations (Dudas, Alazán, San Antonio), which are extended over an area of 300 square kilometers and it is located on the Amazon slope, 2200 meter above sea level. The total installed power capacity is 21 MW and includes horizontal Pelton turbines with height between 195 and 294 meters, a water flow at design conditions between 3 and 4.5 m^3/s, being the average estimated generation a total amount of 125 GWh/year [**27**]. It is expected to be completely operational at the end of 2016. The 3 hydropower exploitations (Fig. 1) are basically composed by intake weir, desander, aqueduct and tunnels (conduction system), forebay tank and its discharge system; penstock and power house.

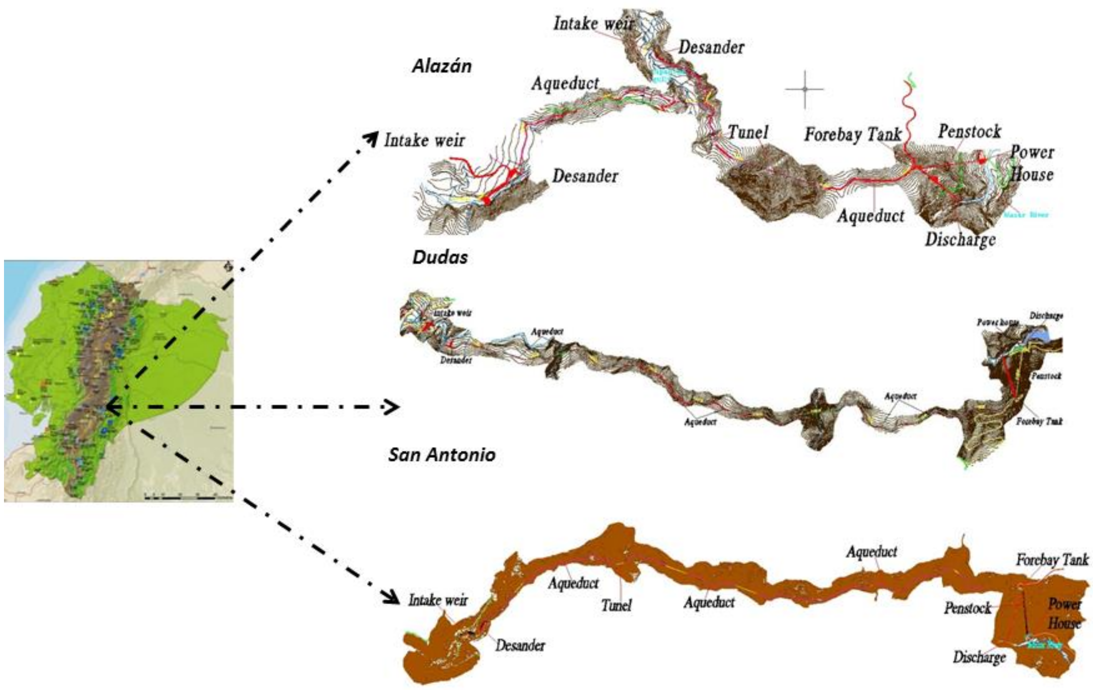

Fig. 1. Mazar-Dudas Hydropower scheme

Baba hydropower plant is the second study case whose installed capacity is 42 MW. It has a drop height of 26 meter, two Kaplan turbines (90 m^3/s each one), and an average annual generation of 161 GWh. It was put into operation in 2013. Moreover, Baba is a multipurpose project: it will guarantee water in dry season for agricultural use, prevent flooding in rainy season and transfer water to Marcel Laniado Wind (M.L.W) hydropower dam (213 MW) in order to increase its annual electricity generation. Due to that water transfer (250 m^3/s of design flow), the other hydropower plant will generate an extra 439 GWh/year on average. Therefore, Baba Hydropower has a total generation of 600 GWh/year, directly and indirectly, coming from its basin and its transfer to M.L.W dam. Its design (Fig. 2) consist on a dam with a maximum water flooded layer of 1100 hectares, 3 channels and 4 dikes, a discharge and transfer channel and two spillways, one located at the dam (flow rate 3700 m^3/s) and the another one located on one side of the power house (flow rate 70 m^3/s) [**28**]. To sum up, it is clear that the design of Baba differs from the common dam hydropower schemes.

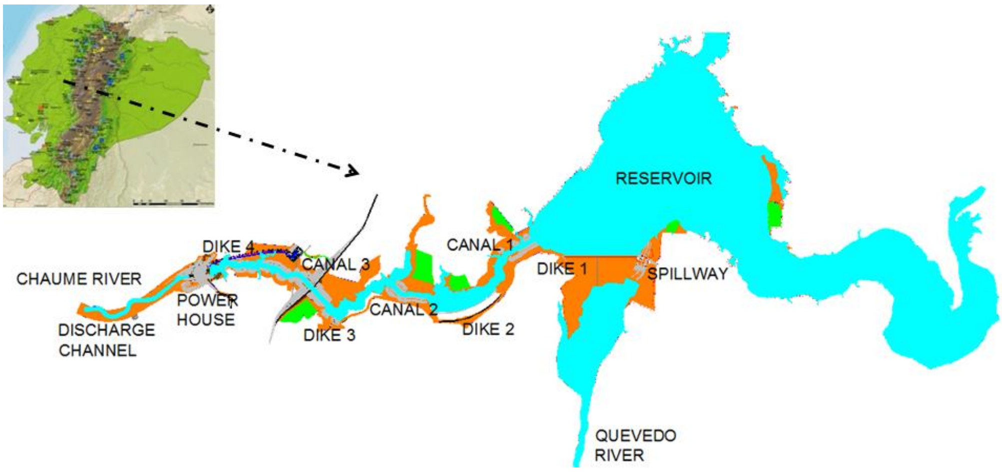

Fig. 2. Baba Hydropower scheme

2.2. Life cycle inventory

2.2.1. Data collection and assumptions

Primary data was mainly collected from the final hydropower plants designs and payrolls, issued by Hidronación [**28**] and Hidroazogues [**27**] [**29**]. Complementary data was obtained from interviews with the staff in charge of the hydropower operation and from government reports. Average fuel consumption and working yield were applied according to the bibliography as well as the type of the machinery (Table 1).

2.2.2. Scope and Functional unit

Due to the types of materials used in the construction, the lifespan of hydropower system is usually high. Commonly, when LCA is carried out, the lifespan for dam hydropower is 100 years while for run-of-river hydropower is usually less than that time [**14**] [**22**]. Therefore, it was determined a lifespan of 100 and 80 years for Baba and Mazar-Dudas hydropower respectively. The functional unit defined in this work is firstly based on the electricity generation. Hence, the functional unit to assess the environmental impact is 1 MWh generated and injected into the grid. Nonetheless, in order to have wider analysis, alternative functional unit were considered as well and presented in section 4.

2.2.3. System boundaries and exclusions

The two hydropower cases selected in this study enclosed in their LCA limits the resource extraction, processing and manufacturing of construction and electro-mechanical equipment materials (away and *in situ*); the transport of all materials (local and from abroad) and internal transportation of the machinery; earth works, and other internal processes; operation, maintenance and replacement of the main electro-mechanical equipment, as well as the transmission system to the electrical substation (Fig. 3). The LCA analyses were divided in two stages or phases: construction and operation and maintenance (O&M). Usually, at the end of the hydropower lifespan, the facilities remains on site since decommissioning may provoke major environmental impacts than the construction itself [**30**] [**10**]. Therefore, in the system boundaries of this LCA study, it was excluded decommissioning as well as workers and equipment transportation, general machinery manufacture, encampment construction and access roads. Particularly, once the operation of hydropower dam scheme has ceased, the reservoir will dry up and water will flow naturally.

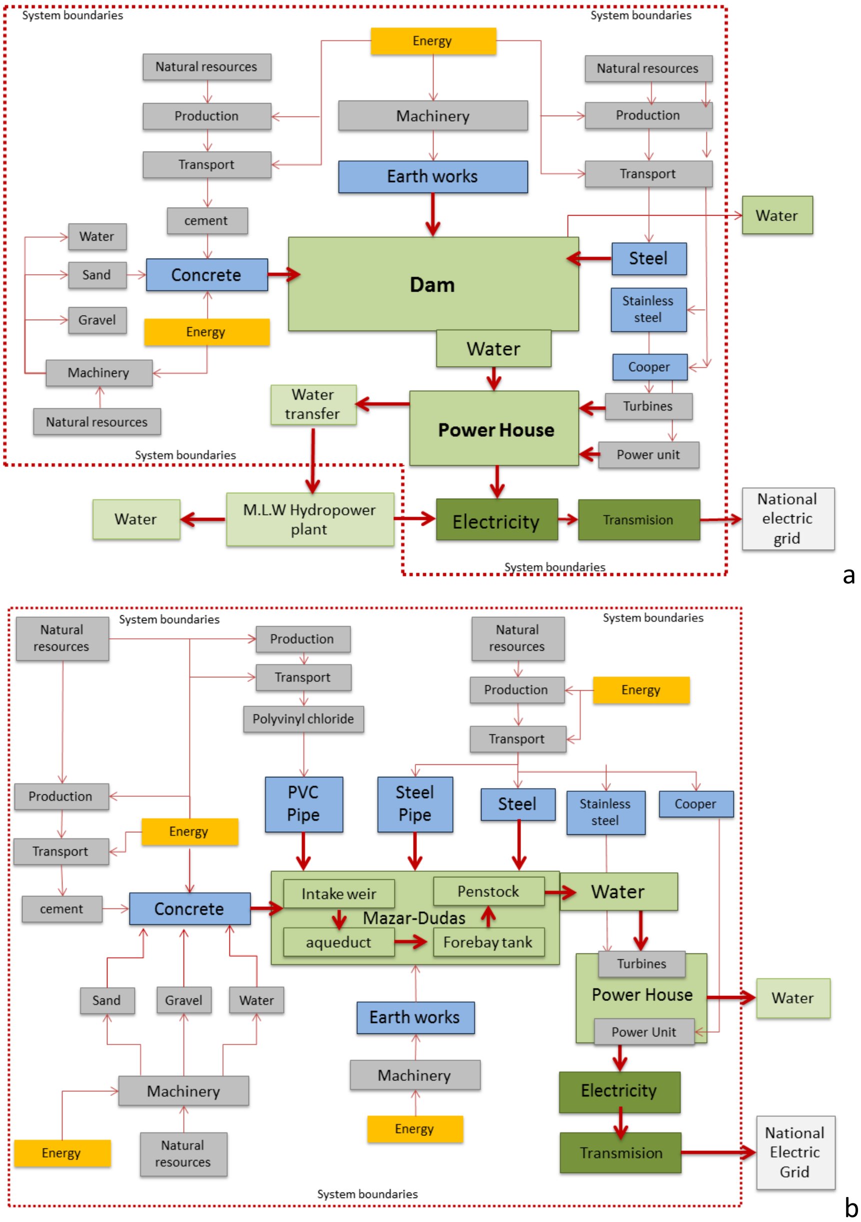

Fig. 3. Baba (a) and Mazar-Dudas (b) Hydropower system boundaries for LCA studies

2.2.4. LCI, Construction phase

The LCI in this stage considers the most representative materials employed in the construction of the hydropower plants: concrete, cement, sand, gravel, water, steel (reinforcing, galvanized, stainless), copper, polyvinyl chloride (PVC), earth works, lubricant oil and energy from the sum of the processes involved (Table 2). Working capacities and yields, fuel consumptions and the emissions *(CO, CO_2, NO_x, SO_2)* of the transport and the earth work machinery were estimated from technical literature (see Table 1 for more details).

Item	***Bibliography***	***Reference Value***
Working capacity	[**31**] [**32**] [**33**] [**34**] [**35**] [**36**] [**37**] [**27**]	8-10m^3 for dumpers; 2m^3 for excavators; 10 m^3 concrete mixer truck
Working yield	[**38**] [**39**] [**40**] [**41**] [**42**]	186 m^3/s for excavators; 43 MJ/m^3 for concrete
Fuel consumption	[**43**] [**44**] [**45**] [**46**] [**47**] [**48**] [**49**] [**50**] [**51**]	182 g diesel/km for dumpers and concrete truck mixer;
Fuel emissions	[**52**] [**53**] [**54**] [**55**] [**56**] [**57**]	5.34 gr CO/kg diesel; 3.14 kg CO_2/kg diésel; 23.63 gr NO_x/kg diésel; 0.24 gr SO_2/kg diésel

Table 1. Reviewed bibliography for LCI machinery

Hydropower plant		***Baba (100 years)***		***Mazar-Dudas (80 years)***	
Input					
Item	***Unit***	***Construction***	***O&M***	***Construction***	***O&M***
Concrete	m³	2.23x10^5	-	2.55x10^4	-
Cement	Kg	6.15x10^7	-	1.01x10^7	-
Sand	Kg	1.95x10^8	-	3.14x10^7	-
Gravel	Kg	2.40x10^8	-	2.41x10^7	-
Water for concrete	Kg	3.16x10^7	-	4.02x10^6	-
Water for electricity	Kg	-	2.48x10^{14}	-	1.90x10^{10}
(Reinforcing) Steel	Kg	1.11x10^7	-	3.32x10^6	-
Earth work	m³	1.57x10^7	-	8.70x10^5	-
Copper	kg	1.48x10^5	2.96x10^5	4.58x10^4	4.58x10^4
Stainless Steel	Kg	2.37x10^4	4.74x10^4	2.10x10^4	2.10x10^4
Lubricant oil	Kg	-	7.90x10^3	-	1.06x10^4
Energy from processes	MJ	6.97x10^8	5.6x10^{-5}	2.80x10^8	5.62x10^{-5}
PVC	Kg	-	-	1.09x10^6	-
galvanized steel	Kg	-	-	7.84x10^3	-
Output					
Electricity	MWh	-	1.61x10^7	-	1.00x10^7
Water for electricity	Kg	-	2.48x10^{14}	-	1.90x10^{10}

Table 2. Baba and Mazar-Dudas hydropower plants Life Cycle Inventory

2.2.5. LCI, Operation and Maintenance phase

In this phase, the electricity generation is performed in the absence of direct GHG emissions to air as it is done by fossil fuel power plants. Despite of this, other emissions were included in the operation of both hydropower plants. On one hand, the spill of oil to water and ground and on the other hand, the emissions to air of SF_6, applied as insulations in high voltage electric systems. For oil and SF_6, it was applied an emission factor reported within previous LCA studies [**14**]. Moreover, it was considered as maintenance the complete replacement of the turbines with their electric parts in each hydropower case and hence stainless steel and copper were assigned in the phase as well as lubricant oil (Table 2). For Baba case, the replacement will be carried out twice in its lifespan (each 35 years) while for Mazar-Dudas once in its lifespan (each 40 years), for stainless steel and copper, considering the worst operating conditions [**14**]. For both cases, lubricant oil will be replaced only once since it has a high durability [**37**]. Commonly, the hydropower LCA studies only considered the impacts associated to already mentioned LCI, but does not take into account GHG emissions from the hydropower reservoir water layer and the loss of their ecosystems. These emissions were therefore analysed accounted for in the following section apart from the life cycle assessment.

2.3. Life Cycle Impact Assessment

2.3.1. Life Cycle with ReCiPe

As impact assessment method which includes several impact categories must be selected in order to perform conventional LCIA stage. After in-depth analysing all the existing methods and considering the significance of their impact categories, geographical approach, evaluation process, scientific soundness and easy interpretation, ReCiPe method (**R**IVM and **R**adboud University, **C**ML, and **P**Ré Consultants)[1] was applied. It is based on CML (Centre of Environmental Science of Leiden University) and Eco-Indicator 99 methodologies, both widely accepted by the scientific community. With a time horizon of 100 years, 10 of its 18 available impact categories were selected (Table 3) for further analysis. The performance of the LCIA stage was supported by SimaPro (7.3 version) software.

Midpoint Impact Category	Unit	Short form
Ozone depletion	kg CFC-11$_{eq}$	OD
Climate change	kg CO_{2-eq}	CC
Terrestrial acidification	kg SO_{2-eq}	TA
Freshwater eutrophication	kg P_{eq}	FE
Freshwater Ecotoxicity	Kg 1.4-DB_{eq}	FET
Terrestrial Ecotoxicity	Kg 1.4-DB_{eq}	TET
Natural land transformation	m^2	NLT
Fossil depletion	kg Oil_{eq}	FD
Metal depletion	Kg Fe_{eq}	MD
Water depletion[a]	m^3	WD
[a]A midpoint life cycle impact category that expresses the total amount of water used, measured in m^3 [**58**]. In the studied case, the water use result in water scarcity due to water transferring.		

Table 3. LCIA Impact categories addressed

2.3.2. Accounting for the net GHG emissions of Baba hydropower reservoir

Findings in the last two decades indicate that hydropower reservoirs produce greenhouse gasses as methane and carbon dioxide, putting into question this generation system as a clean and green electricity source [**59**]. From measurements, several authors have quantified methane and carbon dioxide emissions from hydropower reservoirs located at different parts of the world regions, proving the existence of mentioned gases. For instance, the emissions of GHG from Petit-Saut (French Guiana) [**24**] and Balbina (Brazil) [**60**] tropical hydropower reservoirs were quantified 10 and 18 years after its impoundment. Likewise, others reservoirs located in boreal and non-tropical zones were assessed in those terms [**61**] [**62**]. Particularly, the total GHG emissions of Tucuruí hydropower reservoir (Brazil) [**63**] were estimate from

[1] Institutes that were the main contributors to create the method that provides a "recipe" to calculate life cycle impact category indicators.

others authors data who made measurements 6 and 12 years after the impoundment [**64**] [**65**]. It was also found that some authors have compared these reservoir emissions with fossil fuel thermal power plants, revealing that hydropower reservoir has higher emissions than its fossil equivalent at some point through the life time of the installation [**66**] [**25**].

2.3.2.1. GHG sources and production

As part of dynamic carbon cycle, terrestrial and aquatic ecosystems absorb CO_2, returning some of it back to the atmosphere. In some cases, certain natural aquatic ecosystems may be great producers of CO_2 and CH_4, absorbing low amounts of carbon [**67**] [**68**]. After flooding, a considerable quantity of organic matter stays under water which in the presence of oxygen is decomposed and produces carbon dioxide. Conversely, in the absence of oxygen, the organic matter is decomposed and produces methane gas (through methanogenesis) with a global warming potential 21 times higher than carbon dioxide [**67**] [**69**] [**70**]. Moreover, rivers commonly transport organic matter which contributes with its concentration at the reservoir, giving place to a continuous decomposition and production of the mentioned GHG [**69**]. Thus, as the amount of flooded organic matter increases, GHG emissions also raises up.

The production of CO_2 and CH_4 gases in the reservoirs depends on several factors such as temperature, residence time of the water, reservoir volume, depth and age; quantity of the flooded vegetation, geographic location, etc. In particular, the age of the reservoir, the quantity and type of flooded vegetation play an important role in decomposition ranges [**71**]. Once the organic matter has decomposed, the produced CO_2 and CH_4 reach the water surface layer giving place to the *diffusion* of them into the atmosphere. The methane is also released through bubbles that are produced in the methanogenesis process (*bubbling*). Carbon dioxide has a higher solubility than methane, thus less CO_2 bubbles are produced. Additionally, more gases are released when the water passes through the turbines and by the spillways, due to the change of temperature, pressure and turbulence (*degasification*). Finally, downstream of the river there are emissions by diffusion [**72**]. The previous generated turbulence facilitates the gases to be easily diffused to the air (Fig 4) [**69**]. From the evidence and conclusions made by several authors, the followings observations were considered in order to estimate what would be the emissions from Baba hydropower plant:

- The quantity of GHG would vary from one reservoir to another, even if they are located in similar environmental areas [**69**];
- From the total emissions, 45% would come from the reservoir [**24**], and
- The 55% would come from turbines, spillways and downstream of the river [**63**] [**72**]. This observation is mainly based on 3 reviewed cases. However, others cases were also considered [**73**] [**74**]
- The major emissions would be given in the first 4 years after the impoundment, with a decreasing trend over the time [**75**] [**24**];
- Tropical reservoirs may emit more GHG than boreal ones, especially CH_4 [**76**];
- Several factors may influence on the quantity production of GHG [**69**] [**67**]

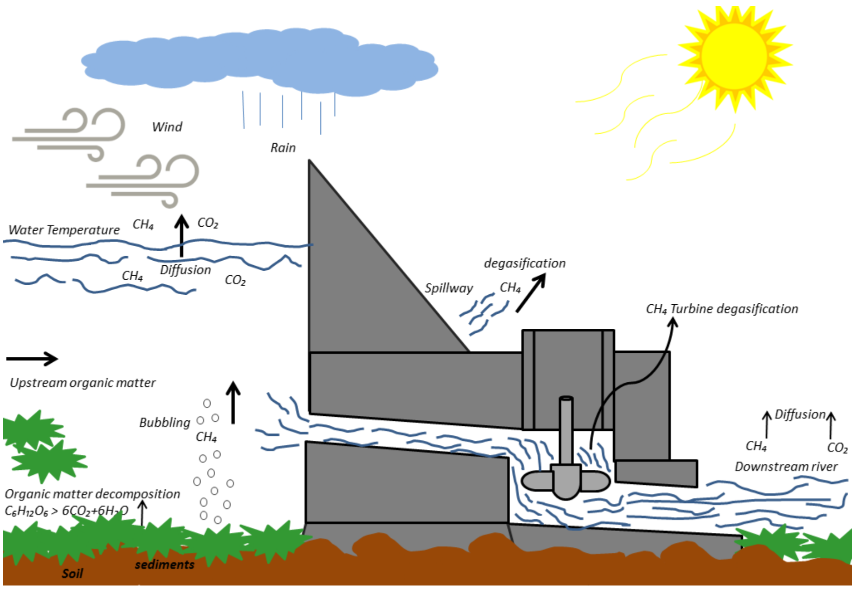

Fig. 4. GHG emissions sources from hydropower dams

2.3.2.2. Assessment and estimate of GHG emissions

In order to estimate the emissions, the differences between *gross* and *net* emissions should be clarified first. Gross emissions are the sum of all emissions without balancing while net emissions are "the difference between pre- and post-reservoir emissions from the portion of the river basin which consider GHG exchanges before, during and after the construction of the reservoir" [**74**]. In this context, when hydropower plants are assessed either through LCA, carbon footprint, or any other environmental approach, emissions sources as reservoir, turbines or river downstream are not included as well as life cycle emissions, depending on the study approach [**77**] [**75**]. Therefore, only gross emissions are showed. In the absence of long-term field measurements, a complete rough and holistic estimate of net GHG emissions per year (E_n) was made considering, among others, the loss of ecosystem (E_e, pre-flooding); the reservoir (E_r) and turbine, spillway and downstream river (E_{tsd}, post-flooding):

$$E_n = E_e + E_r + E_{tsd} + E_{com}$$

The emissions from the construction, operation and maintenance (E_{com}) were determined in the previous LCA section and completed the analysis of emissions. The emissions originated by the loss of the ecosystem (E_e) were based on carbon fixation of the terrestrial ecosystem. As part of carbon cycle, aquatic ecosystems emit CO_2 and CH_4. Any possible emissions from the present aquatic ecosystem (river) were excluded since they are likely to be near zero, due to several factors as water speed, low organic matter concentration, depth, etc. [**77**] [**68**] Accordingly, the photosynthesis and respiration formula was applied to determine the terrestrial ecosystem carbon fixation capacity, through its net primary production [**78**]. Net primary production (NPP) is the difference between gross primary production (GPP) and autotrophic respiration [**79**] [**80**]. For tropical forest, NPP value is 1500 g dry matter/m^2/year [**68**].

$$CO_2(264\ g) + H_2O\ (108\ g)$$
$$\rightarrow C_6H_{12}O_6(180\ g) + O\ (193\ g)$$
$$\rightarrow Amylase\ (162\ g)$$

According to the photosynthesis and respiration formula, plants absorb CO_2 and H_2O, giving as a result glucose ($C_6H_{12}O_6$), oxygen (O_2) and amylase. This last particular element is related to the growth of dry matter. Therefore, to form 1 g of dry matter, it is required 1.63 g CO_2 and released 1.2 g of oxygen [**78**]. The GHG emissions from Baba reservoir (E_r, g $CO_{2\text{-eq}}$/year) were calculated from 3 selected hydropower reservoir cases (Table 4) which have similarities with the presented case as flooded vegetation, weather conditions or geographic location. The emissions were calculated as follows:

$$E_r = E_f \times A_e \times 365$$

Where E_f is the mean reservoir emission factor, expressed in g $CO_{2\text{-eq}}/m^2$/day and A_e, is the reservoir area (1100 ha). Following the field measurements and projections exposed in several studies [**74**] [**66**], each reservoir case was projected using interpolation and exponential function, thus obtaining what would have been the emissions from the year 1 to the latest known emissions (Fig 5). Then, a mean emission factor (E_f) for each year was calculated for Baba reservoir until year 18. From year 19 to 100, it was assumed that the emissions remain equal to those found at year 18. In this context, Zhang et al [**77**] applied directly a constant mean emission factor (2271.6 g $CO_{2\text{-eq}}/m^2$/year) based on the literature.

Reservoir	***Country***	***Zone***	***Land cover***	***Year of field measurements***
Petit-Saut	French Guiana	Tropical	Forest	1, 10
Balbina	Brazil	Amazon	Forest	18
Tucuruí	Brazil	Tropical	Agriculture	6, 12

Table 4. Hydropower reservoir reference cases

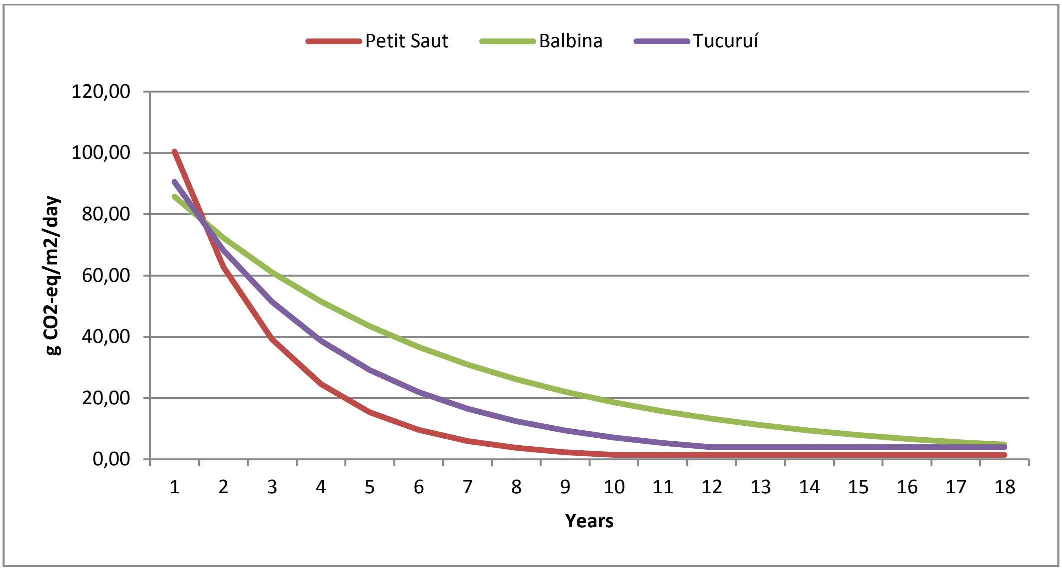

Fig. 5. Trend emissions projections of Petit Saut, Balbina and Tucuruí hydropower reservoir made in this study

Finally, the last emissions come from turbines, spillways and downstream river. These emissions were calculated as follows:

$$E_{tsd} = \left(\frac{E_r \times 55}{45}\right)$$

3. Results Combined LCA

3.1. Life Cycle Assessment, (E_{com})

Life cycle impact assessment was performed with SimaPro Software, applying Recipe midpoint method, world-hierarchist perspective, focusing on the previous selected impact categories. Table 6 summarized the results of Baba and Mazar-Dudas hydropower respectively. The abbreviation of the impact categories was already presented in Table 3.

Baba construction phase accounts for literally 100% of the environmental impacts in 9 of the 10 selected impacts categories (Table 6). The spillway, dike 1 and power house have the major environmental loads due to the intensive use of concrete and cement. This last particular material, which has high energy and material intensity in its manufacture process, is responsible for most of the impacts in OD, NLT, FET and TET impacts. The steel is the second material with major impacts, accounting for 99% of MD impact category. Another material to highlight in this phase is fossil fuel consumption (diesel) used for earth works machinery and transportation. Baba O&M phase accounts for 99% in WD impact category which mainly represents the use of water for generation. Moreover, this phase has also slight impacts on CC, TA and MD (<5%).

Regarding Mazar-Dudas, its construction phase has similarities with Baba hydropower plant in terms of percentages (Table 6). This phase also accounts for 99% of the environmental impacts in 7 impacts categories (FE, MD, FET, TET, NLT, FD, OD) and over 90% in CC and TA categories. Again steel, concrete and hence cement, are the materials with the highest environmental loads. The use of these materials is concentrated on conduction system, penstock and power house in the 3 hydroelectric projects (Alazán, Dudas and San Antonio). The O&M phase only has impact in WD category as Baba, and slightly in CC and TA (7% for both).

Impact Category	Unit	Baba				Mazar-Dudas			
		Total	Construction	O&M	/MWh	Total	Construction	O&M	/MWh
CC	kg $CO_{2\text{-}eq}$	9.29E+07	8.42E+07	8.69E+06	5.77	2.58E+07	2.41E+07	1.71E+06	2.6
OD	kg CFC-11_{eq}	3.75	3.71	0.03	2.3E-7	0.862	0.85	0.0114	8.6E-8
TA	kg $SO_{2\text{-}eq}$	1.97E+05	1.83E+05	1.36E+04	0.01	8.12E+04	7.56E+04	5.64E+03	8.1E-3
FE	kg P_{eq}	1.3E+04	1.30E+04	3.44	8.1E-4	6.77E+03	6.76E+03	4.16	6.8E-4
TET	Kg 1.4-DB_{eq}	4.06E+03	4.04E+03	1.32E+01	2.5E-4	1.24E+03	1.23E+03	7.97	1.2E-4
FET	Kg 1.4-DB_{eq}	3.19E+05	3.19E+05	94.36	0.02	2.13E+05	2.13E+05	97.4	2.1E-2
NLT	m^2	1.14E+07	1.14E+07	24.75	0.71	1.36E+05	1.36E+05	27.8	3.6E-3
WD	m^3	2.4E+11	9.84E+07	2.4E+11	14887	1.89E+10	1.92E+05	1.89E+10	1885.5
MD	Kg Fe_{eq}	1.18E+07	1.13E+07	4.65E+05	0.73	1.27E+07	1.27E+07	8.32E+04	1.3
FD	kg Oil_{eq}	1.42E+07	1.41E+07	1.14E+05	0.88	5.60E+06	5.56E+06	4.37E+04	0.6

Table 6. LCIA Baba and Mazar-Dudas hydropower results

All the specific environmental impacts from Baba are higher than Mazar-Dudas, with the exception of MD where Baba has 0.73 kg Fe_{eq}/MWh while Mazar-Dudas has 1.3 kg Fe_{eq}/MWh. This is mainly due to high requirement of steel for the conduction system of Mazar-Dudas. In terms of CO_2 and CFC emissions, Baba is two and four times higher than Mazar-Dudas respectively. On the other hand, and among the 3 hydropower plants which shape Mazar-Dudas, Alazán has the lowest emissions, followed by San Antonio and Dudas. The latter has the highest power capacity and drop height but the lowest water flow (Table 7) (Fig 6).

MAZAR-DUDAS Hydropower				
Item	***Unit***	***Dudas***	***Alazán***	***San Antonio***
Water flow	m^3/s	3	3.4	4.4
Installed capacity	MW	7.4	6.3	7.2
Mean annual energy	GWh/year	41.4	39.1	44.9

Height	m	294	205	195

Table 7. Mazar-Dudas and its 3 hydropower projects

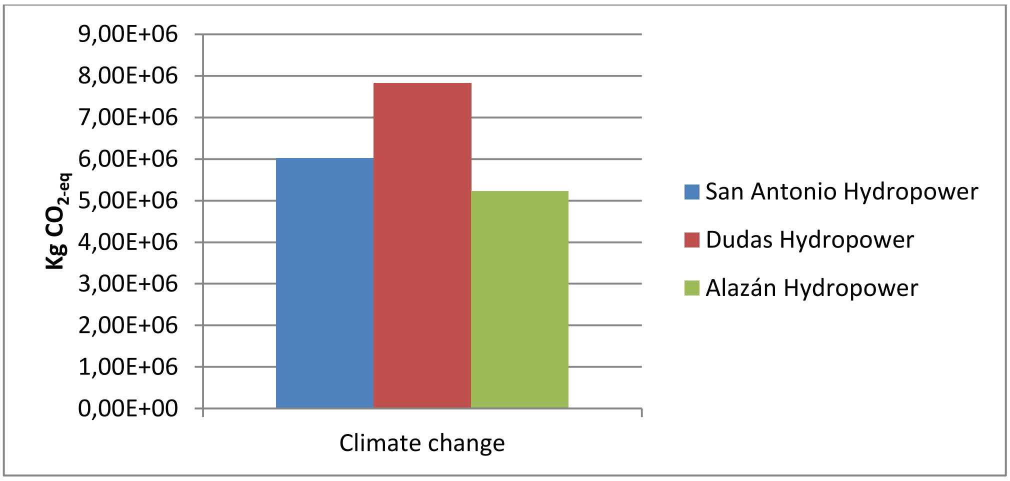

Fig. 6 San Antonio, Dudas and Alazán life cycle emissions comparison

3.1.1. Uncertainty Analysis

Through SimaPro software an uncertainly analysis was carried out, applying Monte Carlo method. SimaPro data base has default uncertainty ranges which allow this analysis. For the 5000 conducted iterations, it was found that Baba has lower ranges of uncertainty than Mazar-Dudas. The results were normalized according to climate change impact category (CO_2 emitted). In both cases, the confidence interval was 95% while the coefficient of variation was less than 5% but up to 50% for Baba and Mazar-Dudas hydropower respectively. Particularly, main standard deviation was found on OD (0.08), TET (184.4) and NLT (235.1) for Baba, and FE (2050), TET (297), FET ($1.2x10^5$) and NLT ($2.33x10^4$) are highlighted in the case of Mazar-Dudas (Fig 7).

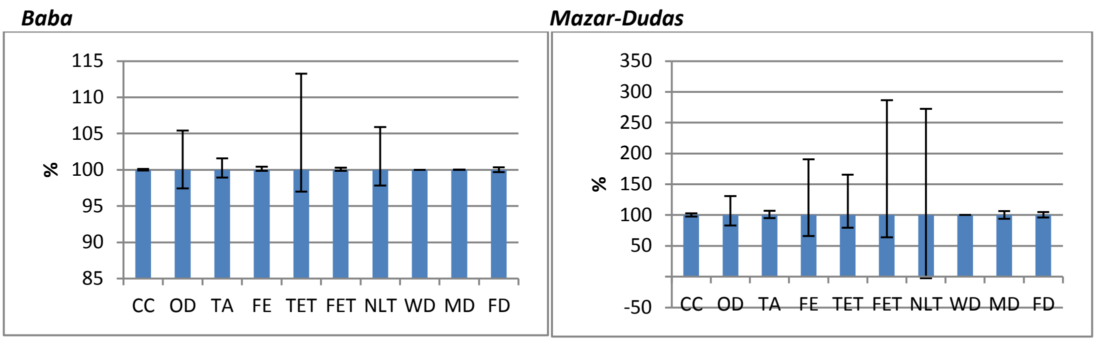

Fig. 7. Standard Deviation results of Baba and Mazar-Dudas hydropower plants

3.2. Net hydropower GHG emissions

Having set the calculation methodology, the net GHG Baba hydropower emissions were estimated. First, the loss of ecosystem (E_e) resulted in 0.02689 Mt CO_2/year[2]. Hence, in the absence of the terrestrial ecosystem, 7335 tons of carbon (*C*) would not be fixed per year on average. Second, the mean emissions factor (E_f) applied to Baba reservoir per year went from

[2] 1 tC = 3.67 t CO_2.

92.28 g $CO_{2\text{-eq}}/m^2$/day to 3.40 g $CO_{2\text{-eq}}/m^2$/day (Table 7). Total emissions are summarized in Table 8, which also includes the emissions from turbines, spillways and river (E_{tsr}) from year 1 to 100. Combining these latest results with LCA emissions (E_{com}), the net lifespan emissions (E_n) were 8.8 Mt $CO_{2\text{-eq}}$, that is, 547 Kg CO_2/MWh on average along its life cycle.

Year	Hydropower Reservoirs			
	Petit-Saut	***Balbina***	***Tucuruí***	**Baba**
1	100.51[a]	85,73	90,61	92,28
2	62.77	72,33	68,22	67,77
3	39.20	61,01	51,36	50,52
4	24.48	51,47	38,67	38,21
5	15,29	43,42	29,11	29,27
6	9,55	36,63	21,92[c]	22,70
7	5,96	30,90	16,50	17,79
8	3,72	26,07	12,43	14,07
9	2,33	21,99	9,36	11,22
10	1,45	18,55	7,04	9,02
11	1,45	15,65	5,30	7,47
12	1,45	13,20	3,99[c]	6,21
13	1,45	11,14	3,99	5,53
14	1,45	9,40	3,99	4,95
15	1,45	7,93	3,99	4,46
16	1,45	6,69	3,99	4,04
17	1,45	5,64	3,99	3,69
18	1,45	4,76[b]	3,99	3,40
19-100	1,45[a]	4,76	3,9927	3,40
All data calculated from [a] [**24**] [b] [**60**][c] [**63**]				

Table 7. Baba reservoir estimate GHG emissions, *g $CO_{2\text{-eq}}/m^2/d$*

Year	*Loss ecosystem (E_e)*	*Construction, O&M (E_{com})*	*Reservoir (E_r)*	*Turbine, spillway and river (E_{tsr})*	*Total Emissions*	*Emission factor*
	Mt CO_{2eq}/year	*Mt CO_{2eq}/year*	*Mt CO_{2eq}/year*	*Mt CO_{2eq}/year*	*Mt CO_{2eq}/year*	*Kg CO_{2eq}/MWh*
1	2.689E-02	9.29E-04	3.7052E-01	4.5286E-01	8.5120E-01	5287
2			2.7210E-01	3.3257E-01	6.3249E-01	3929
3			2.0286E-01	2.4793E-01	4.7861E-01	2973
4			1.5340E-01	1.8749E-01	3.6871E-01	2290
5			1.1754E-01	1.4365E-01	2.8901E-01	1795
6			9.1137E-02	1.1139E-01	2.3035E-01	1431
7			7.1422E-02	8.7288E-02	1.8653E-01	1159
8			5.6500E-02	6.9063E-02	1.5339E-01	953
9			4.5064E-02	5.5078E-02	1.2798E-01	795
10			3.6198E-02	4.4237E-02	1.0825E-01	672
11			2.9983E-02	3.6641E-02	9.4439E-02	587
12			2.4953E-02	3.0502E-02	8.3278E-02	517
13			2.2190E-02	2.7125E-02	7.7137E-02	479

14			1.9858E-02	2.4275E-02	7.1956E-02	447
15			1.7892E-02	2.1872E-02	6.7586E-02	420
16			1.6233E-02	1.9844E-02	6.3899E-02	397
17			1.4833E-02	1.8133E-02	6.0789E-02	378
18			1.3652E-02	1.6690E-02	5.8165E-02	361
19-100			1.3652E-02	1.6690E-02	4.7964E+00	361
Total	2.689	0.0929	2.6961	3.2952	8.8	*547**
*Mean life cycle emission factor						

Table 8. Net emissions of Baba hydropower

4. Sensitive Analysis

4.1. Variable Power Generation

Due to the hydrological seasonality of hydropower generation, the $CO_{2\text{-eq}}$ emissions per electric energy unit (EF_e) could vary. Commonly, hydropower plants have a plant factor over 50% which it is not the case of Baba. If the plant factor of Baba was 65%[3] instead of 44% [**28**], the direct average annual electric generation would be 239.2 GWh/year and hence the emissions would be 368 kg $CO_{2\text{-eq}}$/MWh, a reduction of 33%. The water use for electric generation would be 3,6906x10^9 m^3/year, an increase of 50%, regarding the plant factor of 65%.

The fact that the design of Baba allows transferring water to another hydropower dam (M.L.W, built in 90´s decade) and additional electricity is generated, should also be analysed. If this second generation was considered as *indirect* one, which is 439 GWh/year on average, the sum of direct and indirect generation give a total annual average generation of 600 GWh/year giving place to 147 kg $CO_{2\text{-eq}}$/MWh. However, in this value are not included the emissions originated from the life cycle of the second hydropower plant upon classical LCA approach. Since it is assumed to be an existing facility, independently of Baba, an average EF_e was considered (31 kg $CO_{2\text{-eq}}$/MWh) according to life cycle studies reviewed (see Table 10). Therefore, the new EF_e would be 169 kg $CO_{2\text{-eq}}$/MWh. Anyway, if the generation of M.L.W is included, a reduction of 68% is found in net GHG emissions.

Regarding hydrological variability, the water flow and precipitation of course will vary through Baba lifespan, having either very dry or wet seasons. Assuming a dry year scenario, the average maximum water flow could be 50m^3/s and the precipitation would decrease to the half [**28**] producing a reduction of 50% of electric generation. According to Baba water flow report at historical natural regimes, every 20 years there could be at least one dry year. Therefore, in this scenario, the emissions would be 560 kg $CO_{2\text{-eq}}$/MWh. Following this hydrological analysis, Mazar-Dudas could also be analysed. The effects of climate change here may reduce the glacier water store capacities from the Andes Mountains hence affecting rivers flow. Considering water flow reduction of 10% each 40 years [**81**], Mazar-Dudas would have an EF of 3.2 kg $CO_{2\text{-eq}}$/MWh, a slight increase of 0.24%.

4.2. Baba GHG reservoir emissions compared with tropical hydropower and fossil fueled plants

Several authors have compared the GHG emissions between hydropower reservoir and fossil fuel thermal power plants. Despite of gross emissions consideration, their results show that the cumulated hydropower reservoir emissions may exceed the ones from its thermal

[3] According to the hydropower generation in Equator [**26**]

equivalent based on carbon, oil or natural gas over the time and after 25 years of operation, the emissions would start to equalize [**25**] [**66**]. To compare Baba hydropower with its thermal power plant equivalent (Fuel oil and Natural gas), the emissions were calculated with the plant efficiency and the emissions per thermal energy unit of the used fuel [**74**]:

$$TPPEe = \frac{MAE \times FF_{ef}}{EEF}$$

Where *TTPEe* are the emissions of the Thermal Power Plant Equivalent (Mt CO_2/year), *MAE* is Mean Annual Energy (MWh/year), FF_{ef} is the fossil fuel emission factor (Kg $CO_{2\text{-eq}}$/TJ) and *EEF* is the thermal power plant efficiency (%). As a result, Baba hydropower has lower emissions than its equivalent fuel oil and natural gas power plants (Table 11). The *indirect* generation gives Baba greater environmental performance. However, as it was shown in Table 8, note that in the first 10 years Baba would exceed its equivalent fossil fueled plants emissions.

Power plant	Mean Annual Energy	TPPE emissions	TPPE emission factor
	MWh/year	*Mt CO_2/year*	*Kg $CO_{2\text{-eq}}/MWh_e$*
Baba	161000	0,088	547
Baba[a]	600000	0,101	169
Fuel Oil[b]	161000	0,141	873
Fuel Oil	600000	0.524	873
Gas natural[c]	161000	0.104	647
Gas natural	600000	0.388	647

[a]Mean annual generation considering water transfer and indirect generation of 439 GWh/year; LCA emissions of the second hydropower are included. [b]Fuel oil efficiency (*EEF*): 30%; FF_{ef} =73,300 Kg $CO_{2\text{-eq}}$/TJ. [c]Natural gas efficiency (*EEF*): 33%; FF_{ef} =54,300 Kg $CO_{2\text{-eq}}$/TJ [**25**] [**74**] [**82**] [**83**]

Table 11. Baba emissions comparison with its fossil fuel equivalent power plants.

4.3. Baba Supplementary Services

Besides the electricity generation, Baba reservoir was built for transferring water, guaranteeing agricultural demands and ecological flows in dry season and to prevent flooding in rainy season. Therefore, this hydropower could be also analysed from the water use perspective by applying one cubic meter of water served as new functional unit (FU). Water transfer for electric generation, water supply for ecosystems and agricultural use, are the 3 main Baba services. The mean annual water transfer is 2.77×10^9 m^3 and water supply for ecosystems is 4.97×10^8 m^3/year (10 m^3/s annual constant flow) of which 9.46×10^7 m^3/year are for agricultural use [**28**]. The total mean annual water input is 3.38×10^9 m^3. In order to obtain a new LCI, an allocation coefficient (Ƞ) based on water use percentage, was applied for each service (Table 9).

Input	*Unit*	*Ecosystems (Ƞ=0.15)*		*Agricultural use (Ƞ=0.03)*		*Water transfer (Ƞ=0.82)*	
		*Output**	*/m^3x Ƞ*	*Output**	*/m^3x Ƞ*	*Output**	*/m^3x Ƞ*
Concrete	m^3	4.97×10^{10}	6.73E-07	9.46×10^9	7.07E-07	2.77×10^{11}	6.59E-07
Electricity	MWh		4.86E-05		5.11E-05		4.76E-05
Earth work	m^3		4.74E-05		4.98E-05		4.64E-05
Energy[a]	MJ		2.12E-03		2.23E-03		2.08E-03
Emissions[b]	Kg		2.65E-02		2.79E-02		2.60E-02

*output in m^3 (100 years lifespan). [a]Energy used in processes included in life cycle system boundaries of Baba hydropower. [b]Total life cycle emissions in CO_{2-eq}

Table 9. Baba LCI water perspective

All the LCI results (Table 9) seem to be negligible due to their low values, with a slight different among them. Focus on GHG emissions, agricultural use obtained lightly the highest emissions, with 0.0279 kg CO_{2-eq}/m^3, followed by water for ecosystems with 0.0265 kg CO_{2-eq}/m^3 and water transfer with 0.0260 kg CO_{2-eq}/m^3. Focusing only the comparison in water devoted to be transferred into other basis, these values were contrasted with water transfer reported emissions. For instance, several LCA of water production technologies and water use have been carried out in Spain [**84**] [**85**]. On one case, Ebro River Water Transfer (ERWT) was assessed, obtaining 1.44 kg CO_{2-eq}/m^3, with a water flow of $1x10^9m^3$/year, less than the half of Baba water transfer [**85**]. On another case, it was assessed the environmental impacts of different water supply sources which contribute to meet the demand in Mediterranean water stressed region (Southeast of Spain). To meet the water demand of $1.48x10^9m^3$/year (2015), it was required the participation of Tajo-Segura water transfer (TSWT). Accounting for 27.4% of the total water demand, TSWT obtained 0.70 kg CO_{2-eq}/m^3 [**86**], 25 times higher than Baba water transfer. Despite of this, it should be highlighted that the presented case in this work is less than 9 km and a natural river bed was used to the transfer while TSWT is around 300 km, built with channels and pipelines and more than 900 km in the case of ERWT. Therefore, there is a remarkable difference in terms of construction and distance, besides the water flow. Another example of water transfer was found in California State (USA) that obtained 1.09 kg CO_{2-eq}/m^3 [**87**] higher than the latter case in Spain, with a distance over 400 km. Note that some others water supply alternatives and water treatments like water abstraction were reported with 0.051 kg CO_{2-eq}/m^3, water treatment for drinking 0.219 kg CO_2/m^3 and 0.15 kg CO_{2-eq}/m^3 for transferred water by pressurized pipelines [**88**] [**89**]. Overall results from Baba indicate that the impact due to water use is not significant, since major use of Baba is hydropower generation.

5. Discussion

In terms of emissions, the two presented cases in this work obtained abysmally different results: 547 kg CO_{2-eq}/MWh for dam scheme (Baba) and 2.6 kg CO_{2-eq}/MWh for run-of-river scheme (Mazar-Dudas). With exceptions, hydropower with dam usually has higher emissions than run-of-river schemes, as well as the installed capacity [**18**]. This latter one, plus the height and electricity generation influence on the quantity of CO_2/MWh, especially in small hydropower plants (<50 MW) [**22**]. Even though in some LCA studies decommissioning stage or final disposal was taken into account, Baba hydropower plant differs notably from what has been reported. This is mainly due to the exclusion of the loss of ecosystems and all reservoir emissions in the life cycle assessments, even in studies with different environmental approach as carbon footprint [**90**]. However, those studies whose aims has been to measure and quantify GHG emissions from reservoir, have excluded either the loss of ecosystem, construction or operation and maintenance (O&M) emissions (Table 10). Hence, all LCA and non-LCA studies have only showed gross life cycle emissions.

Regarding the reviewed LCA studies, they were differentiated by what they have included and their approach. Basically, there were two LCA types: with and without decommissioning or final disposal stage (Table 10). Thus, without decommissioning or final disposal stage, emissions ranged from 6 to 44 kg CO_{2-eq}/MWh, with power capacities up to 3600 MW [**91**]. Here it is included carbon footprint analysis which reported 8-15 kg CO_{2-eq}/MWh [**10**] [**90**][4]. For all these cases, a range of 11-20 kg CO_{2-eq}/MWh was estimated [**18**]. Focus on LCA that included decommissioning stage, the emissions started from 4.2 kg CO_{2-eq}/MWh and go up to 62 kg CO_{2-eq}/MWh [**13**] [**20**], 30% higher than the first LCA cases.

Considering non-LCA studies, the emissions of hydropower plants with dam reached even higher values, exceeding those of fossil fuel power plants. However, the reported values only represented the emissions at some point in the lifespan. According to this, the emissions ranged between 97 and over 5000 Kg CO_{2-eq}/MWh depending on their location (boreal or tropical zone) and the time after impoundment (Table 10) [**71**] [**76**] [**74**]. In hydropower boreal reservoir, up to 671 kg CO_{2-eq}/MWh have been reported, which includes the loss of the ecosystem [**75**]. Tropical hydropower reservoirs emissions went further, up to over 5000 kg CO_{2-eq}/MWh [**24**] [**60**] [**74**]. Despite of this, it is must be said that the emission ranges are slanted, due to the variations of the emissions through the time and the power generation. Therefore, any comparison would be relative. Moreover, in these cases, only gross emissions are exposed, since certain sources of emissions are excluded.

Thus, Baba hydropower plant should only be compared with studies where at least reservoir emissions where considered. For instance, Petit-Saut hydropower tropical reservoir emitted 2027 kg CO_{2-eq}/MWh on average, in its 10 first years after its impoundment [**24**], 3.7 higher than Baba. However, the mean life cycle emissions of the hydropower boreal reservoir (158 kg CO_{2-eq}/MWh) were 3.5 times lower than Baba [**75**]. If the indirect generation (with its life cycle emissions) of Baba is included, its mean life cycle emissions would be 169 kg CO_{2-eq}/MWh, much closer to boreal reservoir emissions, but still far from the common LCA emissions.

Reference	*Study approach*	*Construction and O&M stages*	*Decommissioning*	*Reservoir emissions*	*Scheme*	*Installed capacity (MW)*	*Kg CO_{2-eq}/MWh*
[**16**]	LCA	x			Run-of-river	9	1,2
This study	LCA	x			Run-of-river	21	2.6
[**11**]	LCA	x			Run-of-river	Several	4.9
[**13**]	LCA	x	x		Run-of-river	8.6	4.1
					Dam	95	4.2
[**18**]	LCA	x	x		Run-of-river	Several	2-5
[**92**]	LCA	x	x		Dam	30.3	5.47
[**91**]	LCI	x			Dam	3600	6
[**13**]	LCA	x	x		Dam	175.6	8.3
[**93**]	LCA	x			Run-of-river	0.05-0.1-0.65	5.5-8.9
[**23**]	LCA	x			Run-of-river	3.1	10
[**10**]	CF[A]	x			Dam	5850	8-11
[**11**]	LCA	x			Dam	Several	0.2-11.2
[**94**]	LCA	x	x		Run-of-river	10	11.3
[**22**]	LCA	x	x		Dam	16	13
[**90**]	LCA	x		x[B]	Dam	Several	15
[**22**]	LCA	x	x		Run-of-river	22	18
[**76**]	Unknown	-			Unspecified	Unspecified	4-18
[**18**]	LCA	x			Dam	Several	11-20
[**12**]	LCA	x	x		Run-of-river	1-5	11-23
[**2**]	Unknown				Unspecified	Unspecified	28
[**95**]	LCA	x			Dam	3,2	28.4
[**96**]	LCA	x	x		Dam Run-of-river	Unspecified	1-34
[**20**]	LCA	x	x		Deviation channel	Several	33-43
[**91**]	LCI	x			Dam	44	44
[**21**]	LCA	x			Unspecified	Unspecified	2-48
[**17**]	LCA	x	x		Run-of-river	0.003	52.7

[4] It includes reservoir emissions.

[**20**]	LCA	x	x		Dam	Several	31-62
[**19**]	LCA	x			Unspecified	Unspecified	2.2-74.8
[**20**]	LCA	x	x		Run-of-river	Several	18-75
[**71**]	Unknown	-			Run of river	Unspecified	0.5-152
					non-tropical dam		
					boreal reservoir	Unspecified	160-250
[**97**]	Unknown			x	Dam	Unspecified	397-539
[**98**]	CB[E]			x	Dam	33	494.9
This study[C]	LCA	x		x	Dam	42	547
[**75**]	CF[D]			x	Dam	485	147-671
[**24**]	CB[E]			x	Dam	115	2027
[**71**]	Unknown	-			Tropical reservoir	Unspecified	1300-3000

[A]Carbon Footprint. [B]Turbine, spillway and river emissions not included as well as the loss of ecosystem. [C]Net life cycle emissions. [D]Carbon Footprint boreal reservoir. The study only includes pre-flooding emissions (loss of ecosystem) and reservoir emissions. [E]Carbon budget. Reservoir, turbine, spillway and downstream river emissions considered. Loss of ecosystem and construction emissions excluded. The emission factor consider only 10 years of measurements.

Table 10. Hydropower Life cycle emission factor from literature

On the other hand, it was found that Mazar-Dudas hydropower plant is within the reported range of 2-5 Kg CO_{2-eq}/MWh [**18**] (Table 10). This result is more adjusted to the LCA reported emissions. Despite of this, the emissions vary widely from one case to another. The LCA studies based on construction and O&M stages, reported emissions from 1.2 to 10 Kg CO_{2-eq}/MWh, with capacities below 10 MW [**16**] [**23**]. However, with the inclusion of the decommissioning or final disposal stage in the LCA, the emissions start from 4.1 Kg CO_{2-eq}/MWh and go up to 75 Kg CO_{2-eq}/MWh, whose installed capacities reached 22 MW [**13**] [**17**] [**20**]. Thus, it seems that decommissioning stage increase considerably the emissions up to 86%, according to what have been reported. Taking into account that last fact, and although it has 21 MW, Mazar-Dudas obtained a very low life cycle emission value, being one of the best scores (Table 10).

6. ***Conclusions***

Through a complemented LCA approach, two hydropower schemes located in Ecuador were assessed in order to know their environmental performance, especially their life cycle emissions by means of the different pollution mechanisms. As first conclusion, it was found that there is a lack of LCA studies which fully determine the net life cycle emissions of hydropower, especially those ones associated to an existing reservoir. Regarding this work, its main findings support that hydropower environmental impacts should be taken into account in the decision-making, especially with the development of new dam hydroelectric projects. The run of river scheme (Mazar-Dudas) by far has better environmental performance than dam scheme (Baba). Bearing in mind the rough estimate of reservoir emissions, the major relevance is found in this ambit, since dam scheme obtained 547 Kg CO_{2-eq}/MWh while run-of-river 2.6 Kg CO_{2-eq}/MWh. Despite of these significant emissions by dam scheme case, it is still better option than fossil fueled power plants. Moreover, with the reviewed literature, it was verified that life cycle emissions vary from one place to another which makes each case unique. Taking into account that the reservoir emissions and loss of ecosystem accounts for 99% of the total emissions, future life cycle assessment must consider them, otherwise, their results may be misleading for hydropower dam schemes. In the near future, long-term measurements must be made to clarify and accurate the emissions from reservoir, turbines, spillway and river of Baba hydropower, in order to verify or not its green credential. Finally, it is worthy to note that some other local environmental aspects related to hydropower as water continuity in the river bed, water quality, the transport and supply of nutrients, local eutrophication and aquatic life assessment were not assessed in this study mainly due to the absence of local data and the difficulty of translating their main indicators into equivalent emissions. Moreover, social aspects have not been included so that future works should be done in order to balance the hydropower projects in terms of sustainability.

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