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On the Potential Environmental Repercussions of Hydroelectricity: A Contribution Based on Life Cycle Assessment of Ecuadorian Hydropower Plants

Potenciais Repercussões Ambientais da Hidroeletricidade: Uma Contribuição Baseada na Avaliação do Ciclo de Vida de Usinas Hidrelétricas Equatorianas

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The share of world energy consumption for electricity generation by source is primarily based on coal and natural gas. Within the last years, governments have implemented policies to promote investment in renewable energy. In Ecuador, the share of hydroelectricity has rapidly increased without regarding long-term environmental impacts. This paper aims to develop a cradle-to-gate life cycle assessment of two representative plants of Ecuador (*Agoyán* and *Paute*, with 156 MW and 1075 MW of installed capacity, respectively). The life cycle inventory contains the primary flows of energy and matter during the construction, operation, and final disposal stages, with 1 kWh as a functional unit. The life cycle impact assessment uses the CML 2000 midpoint potential categories, including Abiotic Depletion, Acidification, Eutrophication, and Global Warming. The construction stage is the leading contributor to the global impacts, and the dam the environmental hot spot of both plants, and the reservoir flooding represents the major contributor to the impact during the operation stage. Furthermore, electricity generation in plants with a larger scale can lead to fewer impacts, suggesting that constructing large-scale plants can reduce the global impacts in countries with similar hydropower potential. This methodological framework serves as a decision-making criterion for evaluating the environmental performance of other renewable energy systems.

Keywords: Environmental impacts; hydroelectricity; Life Cycle Assessment; renewable energy.

1. Introduction

Electricity plays a fundamental role in modern society and is a mainstay of the worldwide manufacturing industry. While the consumption of primary energy has doubled since the early 1970s, electricity consumption has increased almost fourfold.[1] The energy sector can contribute to sustainable development given its vital role in economic and industrial activities and basic human needs. However, both energy conversion and consumption go along with environmental, social, and economic concerns such as climate change, increasing energy costs, and security of energy supply[2]. As reported by the OECD,[3] in 2018, hydroelectricity contributed to more than 15% of electricity generation worldwide, and, by 2040, based on the current policies scenario, it shall contribute to more than 33%. They also stated that energy demand should rise by 1.3% each year to 2040, with increasing demand for energy services unrestrained by further efforts to improve efficiency. Environmental impacts associated with electricity have attained critical importance, and Life Cycle Assessment (LCA) has been extensively applied to analyze the environmental performance of electricity all over the world.[2,4,5]

Ecuador has undertaken a significant energy transition to replace nearly all of its fossil-fuel-powered electricity generation with renewable sources. In 2012, hydroelectricity supplied 62% of the country's electricity demand, with the rest coming mainly from thermal generation. By 2022, Ecuador expects to have installed an additional 2 794 MW toward the goal of generating 92.5% of the electricity system from hydropower[6,7] (see Figure 1).

In agreement with the OECD,[3] by 2019, Ecuador was the seventh-largest producer of hydroelectricity by installed capacity, i.e., 556 MW. It is crucial to analyze the potential environmental impacts of the existing infrastructure to reinforce their environmental hot spots. The results of this work will serve as decision-making criteria for constructing sustainable facilities in the long term.

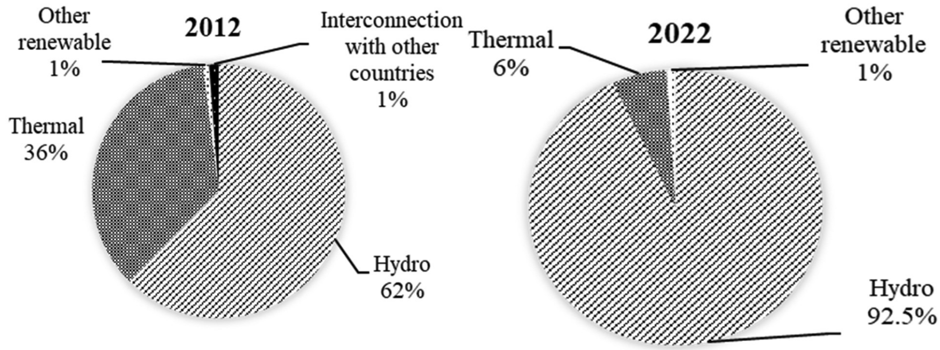

Figure 1. Ecuadorian electricity system (2012-2022). Adapted from.[6, 7]

2. Methodology

An LCA consists of four phases, i.e., goal definition and scoping, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation[8,9].

2.1 Goal definition and scope

The goal definition and scoping show the characteristics of the systems, the functional unit, and the boundaries. This study analyzes environmental performance quantitatively from cradle to gate of hydroelectricity generation in Ecuador by studying the potential impacts of representative plants.

The product systems were determined with the following criteria: years of operation, type of reservoir, and installed capacity. As shown in Table 1, hydroelectricity generation in Ecuador is characterized by a considerable quantity of plants with less than 100 MW and a few large-scale plants, which are the main contributors to the electricity system. By 2022, Ecuador will increase the number of large and medium-scale plants, which will be represented by the systems under study. Among the hydropower facilities of Ecuador, the *Agoyán* and *Paute* plants have the largest database available for analysis.

Considering that electricity generation is the function of the systems under study, the functional unit should be 1 kWh of electricity generated, as recommended by the literature.[9, 10] We assume that the operational time of the systems is necessary to ensure that at the end, the plants will be operating.[10] Fifty years of operation (i.e., *Agoyán* (1988- 2038) and *Paute* (1992- 2042)) is a reasonable life span, considering the Ecuadorian policies scenario. The plants are assumed to become inert waste at their end of life instead of being dismantled.

2.2. Product system spatial boundaries

The life cycle of the systems consists of three stages: construction, operation, and final disposal. The life-cycle inventory includes the primary flows of energy and matter of the plants was elaborated with data provided by the Ecuadorian Agency for Regulation and Control of Electricity[7]. Although different data sources were used, the inventory was adapted for the Ecuadorian context and follows the requirements of the Ecoinvent 3.2 database, available in SimaPro 8 Ph.D., as possible[11].

The construction stage comprises the most relevant civil works. The selection of the most relevant inputs and outputs follows the suggestions of several previous studies.[9,10,11] The product disaggregation and the selection of the most relevant unit processes, i.e., dam, headrace, penstock, powerhouse, surge tank, tailrace, and turbines, during the construction stage was carried out by analyzing design and construction reports, turbine catalogs, and construction standards. The spatial boundaries of the systems are presented in Figure 2.

2.3. Assumptions of this study

Certain elements are challenging to quantify or are insignificant.[9,12,13] The materials and energy present in small quantities (e.g., construction machinery and maintenance equipment) were not considered in this study. Drastic meteorological variations were not considered. The emissions from the reservoir flooding were computed with the model proposed by Hertwich[13].

Table 1. Perspective of the hydropower facilities of Ecuador (2013-2022)[6, 7]. R = run-off-river type, S = storage type.

Scale	Plants 2012 (MW / reservoir)	New plants by 2022 (MW / reservoir)
Large (>100 MW)	*Paute* (1100 MW / S) *Agoyán* (160 MW / R) *San Francisco* (230 MW / R) *Marcel Laniado* (213 MW / S) *Mazar* (184 MW / S)	*Coca-Codo Sinclair* (1500 MW / S) *Paute-Sopladora* (487 MW / S) *Toachi-Pilatón* (276 MW / R) *Minas-San Francisco* (253 MW / R) *Delsi Tanisagua* (116 MW / S)
Medium (30 < MW < 100), small, mini and micro (0.005< MW <30)	11 state and 39 private medium, small, mini and micro plants	*Manduriacu* (60 MW / R)

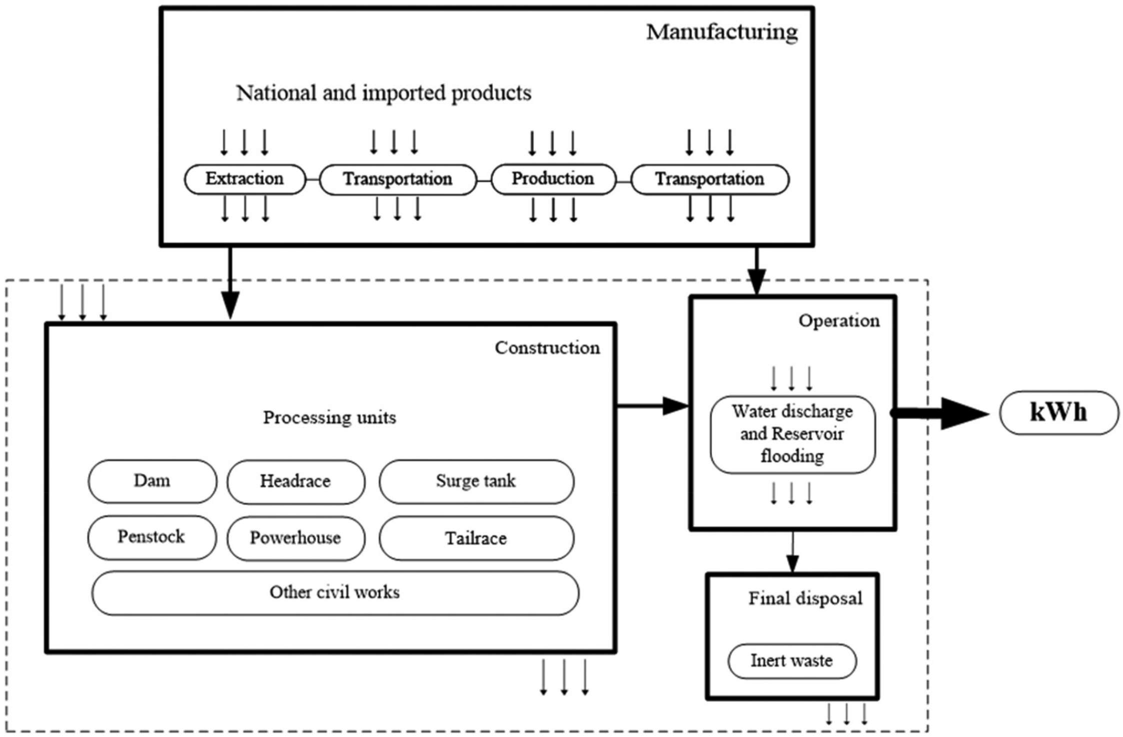

Figure 2. Simplified systems boundaries.[8,9]

2.4. Selection of the impact assessment method and indicators

The impact assessment contains the evaluation of the potential impacts. The CML 2000 method[14] with the aid of the software SimaPro 8 Ph.D., was used for computing the impacts. The impacts were quantified by potential emissions to air, water, and soil using the following potential categories: abiotic depletion for elements (ADP_e) in kg Sb, abiotic depletion for fossil fuels (ADP_f) in MJ, global warming (GWP) in kg CO_2, ozone layer depletion (ODP) in kg CFC-11, photochemical oxidation (POCP) in C_2H_4, acidification (AP) in kg SO_2, and eutrophication (EP) in kg PO_4.

3. Results and Discussion

The results are organized into two parts: (i) the global impacts and hot spots (Sections 3.1-3.3) and (ii) the validation of the primary flows of energy and matter and carbon dioxide emissions with the literature (Section 3.4).

3.1. Global impacts

As reported in previous studies,[9-11,15] the construction stage is the main contributor to the global impacts. According to GWP, the emissions of kg CO_2 eq./kWh during the construction of *Agoyán* (see Figure 3) are

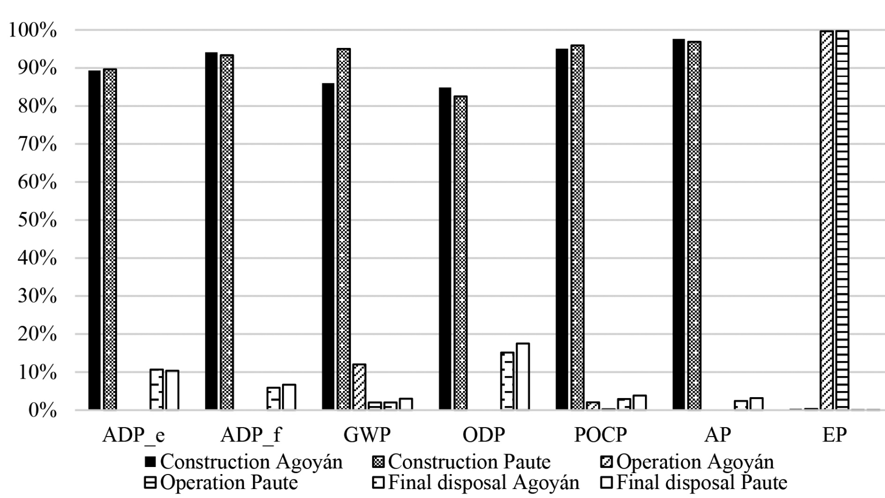

Figure 3. Global impacts by stages.

higher than *Paute,* and *Agoyán* produces less impact than *Paute,* according to ADP_e, as expected. Figure 4 depicts a reduction of the emissions of CO_2/kWh, in line with GWP, with an increase in the scale of generation.

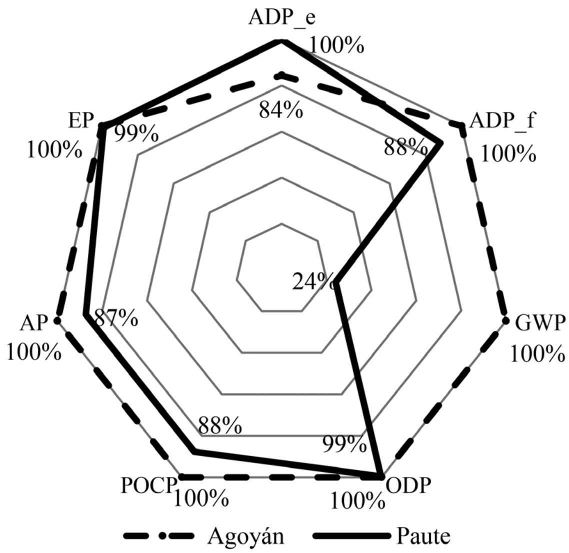

Figure 4. Comparison of global impact, with *Agoyán* as reference.

3.2. Impacts of the construction stage

As shown in Figure 5, the larger scale of generation, the fewer impacts the plant produces according to most categories. As shown in Figure 6, the construction of the dam, the hot spot of both systems, produces the highest impact according to ADP_e, ODP, POCP, AP, and EP due to a large amount of energy and materials consumed, i.e., cement gravel, diesel combusted, reinforcing steel and sand.

3.3. Impacts of the operation and final disposal stages

As illustrated in Figure 3, the operation stage is responsible for the emissions of kg phosphate (PO_4) eq. /kWh from the reservoir flooding, in agreement with EP. The

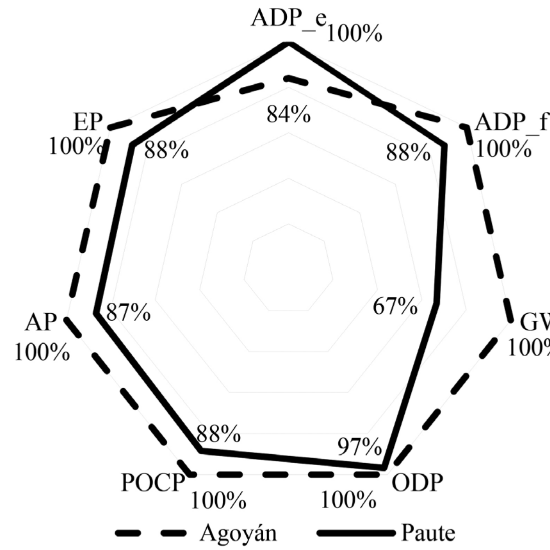

Figure 5. Comparison of impacts of the construction stage, with *Agoyán* as reference.

emissions from the reservoir flooding are the most critical contributors to GWP during the operation. The water discharge is responsible for the increase of kg SO_2/kWh emissions, according to AP. Despite the reservoir flooding emissions, mainly from storage-type plants, the operation does not represent an essential contributor to the global impact (see Figure 4). The final disposal stage does not produce significant impacts because the plants become inert waste at the end of their lives.

3.4. Validation of the results

The inventory was formulated with the primary flows of energy and matter. As summarized in Table 2, the inventory and impact assessment results are in good agreement with similar studies. The materials used during the construction stage decrease with an increase in the installed capacity are shown in Figure 7.

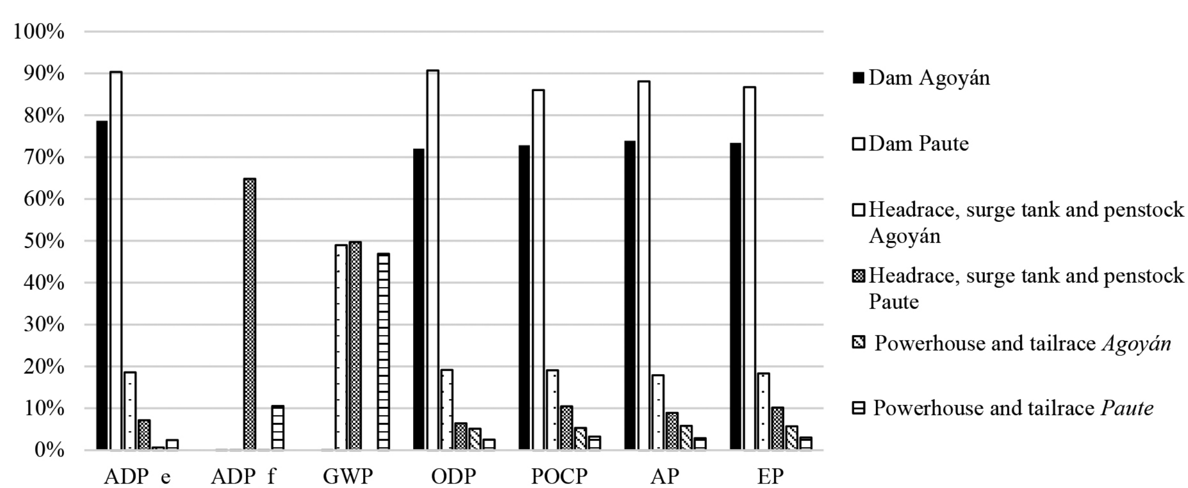

Figure 6. Impacts of the construction of the most relevant unit processes.

Table 2. Summarized inventory and potential impacts of different plants. R = run-off-river type, S = storage type

Plant	Reservoir[1]	Time horizon [years]	Capacity [MW]	CO_2/kWh	Materials [g/kWh]			
					Cement	Water	Sand and gravel	Steel
Agoyán (Ecuador)	R	50	150	18.20	1.40	0.94	8.30	0.10
Paute (Ecuador)	S	50	1100	3.18	1.32	1.16	10.0	0.13
Itaipu Binacional (Brazil)[10]	S	100	14 000	1.56	0.28	0.24	0.41	0.09
Nam Man (Thailand)[15]	R	50	5.10	11.00	4.54	2.27	24.30	0.47
Nam San (Thailand)[15]	R	50	6.00	23.00	6.34	3.17	33.90	1.05
Nam Pai (Thailand)[15]	R	50	2.50	16.30	6.54	3.27	34.40	0.97
Nam Thai (Thailand)[15]	R	50	2.25	22.70	7.02	3.51	37.2	1.66
Nan Ya (Thailand)[15]	R	50	1.15	16.50	5.72	2.86	30.3	0.80

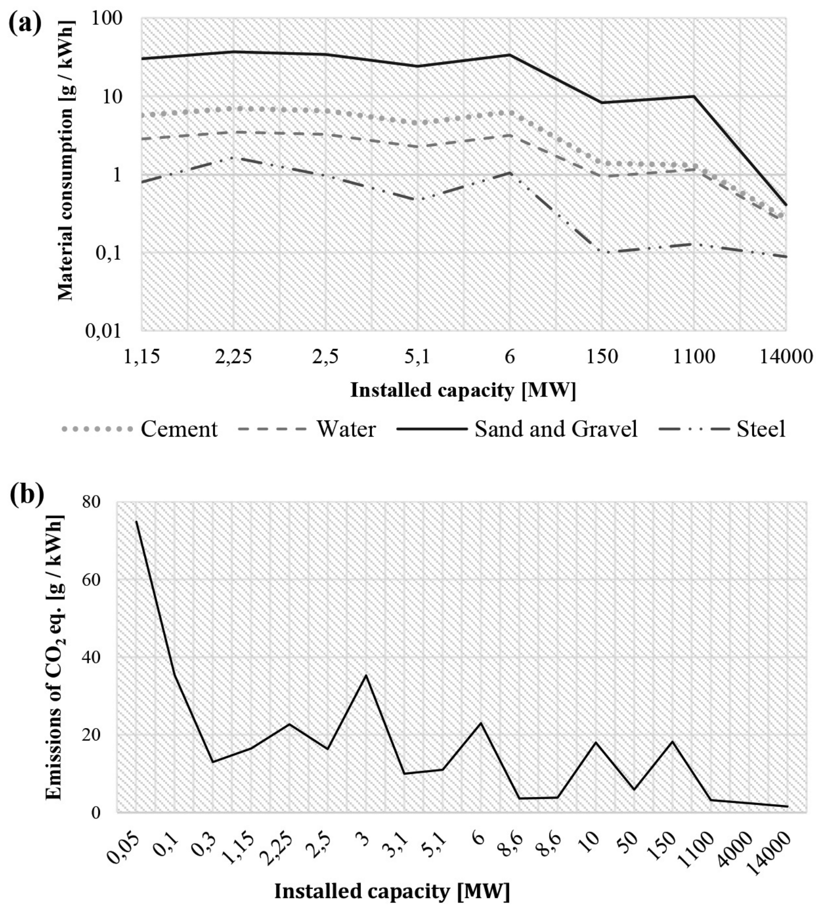

Figure 7. Effect of the installed capacity of hydropower plants on: a) material consumption per kWh in the construction stage, and b) emissions of CO_2 eq./kWh[2]. The data corresponds to Table 2.

4. Conclusions

According to most CML categories, the construction stage, specifically the dam, is the main responsible for the global impacts. The consumption of gravel is the main contributor to kg Sb eq./kWh emissions (ADP_e), and the consumption of cement is the principal responsible for kg. CO_2 eq./kWh emissions (GWP). During the operation stage, the discharge of water from the turbine is related to EP due to the phosphates and nitrates found at the outlet of the discharge tube. The emissions from the reservoir flooding are the main contributors to the CO_2 eq./kWh emissions (GWP). Considering the same time horizon (50 years) and functional unit (1 kWh), *Agoyán* produces higher impacts than *Paute*. Larger scale plants can produce lower potential impacts per functional unit because of the energy generated during their lifetime.

Although an increase in the installed capacity of the plants implies a decrease in the potential impacts, the effect of the emissions of kg PO_4 eq./kWh from the reservoir flooding to the EP should be analyzed depending on the dimensions of the reservoirs. Additionally, emissions of kg CO_2 eq./kWh are reduced with an increase of the installed capacity, neglecting the type of reservoir or time horizon.

It is essential to improve the processes involved in the construction and operation stages of hydropower plants to increase time horizons and lower their global impacts. The design and maintenance plans of the plants should be reformulated to reduce the materials and energy consumption during the construction phase. Finally, the methodology developed in this work can serve as a decision-making criterion for evaluating the environmental performance of hydroelectricity and other renewable energy systems.

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