



Life cycle assessment of run-of-river hydropower plants in the Peruvian Andes: a policy support perspective

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Abstract

Purpose Low-carbon emissions are usually related to hydropower energy, making it an attractive option for nations with hydropower potential as it enables them to meet increasing electricity demand without relying on burning fossil fuels. In fact, the new wave of hydropower plant construction is occurring mainly in tropical areas where an additional environmental impact must be considered: biogenic greenhouse gas (GHG) emissions due to the degradation of biogenic carbon in reservoirs. Peru is planning to install up to 2000 MW in hydropower until 2021, but the input and output flows, as well as the environmental impacts that these generate, have not been explored. Hence, a set of three hydropower plants built in the past decade located in the Peruvian Andes were analyzed from a life cycle perspective. The main objective of the study is to generate detailed life cycle inventories for each of these three hydropower plants with the aim of obtaining specific information for current conditions in Peru.

Methods The life cycle assessment methodology was applied to compute the environmental impacts. Data collection was based mainly on primary data obtained directly from the hydropower companies, although biogenic emissions were modeled considering local net primary productivity conditions and other site-specific conditions. Although the calculation of GHG emissions related to hydropower plants was a priority, considering the important policy implications of decarbonizing the Peruvian electricity grid, other environmental categories, such as eutrophication or the depletion of abiotic resources, were also considered. The IPCC method was used to calculate GHG emissions, whereas a set of eight additional impact categories were computed using the ReCiPe 2016 method.

Results and discussion Results show that GHG emissions per unit of electricity generated were in the lower range of emissions observed in the literature, in all three cases below 3 g CO₂eq/kWh. Biogenic emissions represented less than 5% of the total GHG emissions despite their location in a tropical nation, due to the arid conditions of the landscape in the Andean Highlands, as well as the mild temperatures that are present in the reservoirs. In terms of stratospheric ozone depletion, a GHG with ozone depletion properties, N₂O, was the main source of impact.

Conclusions The results are intended to be of utility for an array of applications, including relevance in decision-making in the energy sector and policy-making at a national level, considering the implications in terms of meeting the nationally determined contributions to mitigate climate change in the frame of the Treaty of Paris.

Keywords Biogenic emissions · Electricity · Industrial ecology · LCA · Peru · Run-of-river hydropower plants

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1 Introduction

According to the latest report by the World Energy Council (WEC), hydropower accounts for approximately 16.4% of worldwide electricity generation, representing over 70% of total renewable energy (WEC 2016). However, the distribution of hydropower plants throughout the world is uneven, with many countries relying almost entirely on this source of electric energy (e.g., Costa Rica, Norway, Brazil, Paraguay, or Ethiopia), whereas other nations, mainly the small Caribbean

islands or those nations situated in arid areas of the world, lack this type of infrastructure. In this context, a notable fact, according to the International Commission on Large Dams (ICLD), is that only 22% of the world's technically feasible hydropower potential was being exploited as of 2011 (ICLD 2011).

The low-carbon emissions that are usually related to this source of energy are making it an attractive option for nations with hydropower potential to meet increasing electricity demand without having to rely on burning fossil fuels (Pehnt 2006). In fact, Zarfl et al. (2015) inventoried up to 3700 major dams worldwide with a capacity above 1 MW that were either under construction or planned by 2040. Most of these are in emerging or developing countries, increasing global hydroelectricity capacity by approximately 1700 GW. In this context, it is plausible to assume that managing the water–energy nexus will be a critical aspect to attain sustainable development in the twenty-first century (Lee et al. 2018; Liu et al. 2018; Srinivasan et al. 2018). For this, progress in water-based energy will have to focus on obtaining energy with increasing dexterity while minimizing habitat disruptions in natural environments (Chu and Majumdar 2012; Conway et al. 2015).

However, the development of new hydropower plants is controversial due to the overestimation of economic benefits, while comprehensive effects on biodiversity are either unknown or purposely omitted (Winemiller et al. 2016). Erosion, changes in sedimentation cycles, losses in river connectivity, reduction of fish diversity, loss of rainforest, alterations in floodplain geomorphology, and algal blooms are just some of the long list of environmental impacts that may be triggered by the proliferation of new hydropower plants (Hertwich 2013; Abd-El Monsef et al. 2015; De Faria et al. 2015; Deemer et al. 2016; Rubio et al. 2017). Considering that the new wave of hydropower plant construction is occurring mainly in three tropical river basins—Amazon, Congo, and Mekong, which are also the most biodiverse catchments in the world—an additional environmental impact must be considered: biogenic greenhouse gas (GHG) emissions due to the degradation of biogenic carbon in reservoirs (Hertwich 2013). For instance, some measurements in the Amazon basin in French Guyana or Brazil have suggested that by including biogenic methane and carbon dioxide in the life cycle emissions of some tropical reservoirs, the final GHG emissions per kilowatt hour produced may be as high as those linked to a coal-fired thermoelectric power plant (Gagnon and van de Vate 1997; Abril et al. 2005; Kemenes et al. 2007). Furthermore, Hertwich (2013) estimated the average worldwide biogenic GHG emissions from hydropower plants as 161 g CO₂eq/kWh.

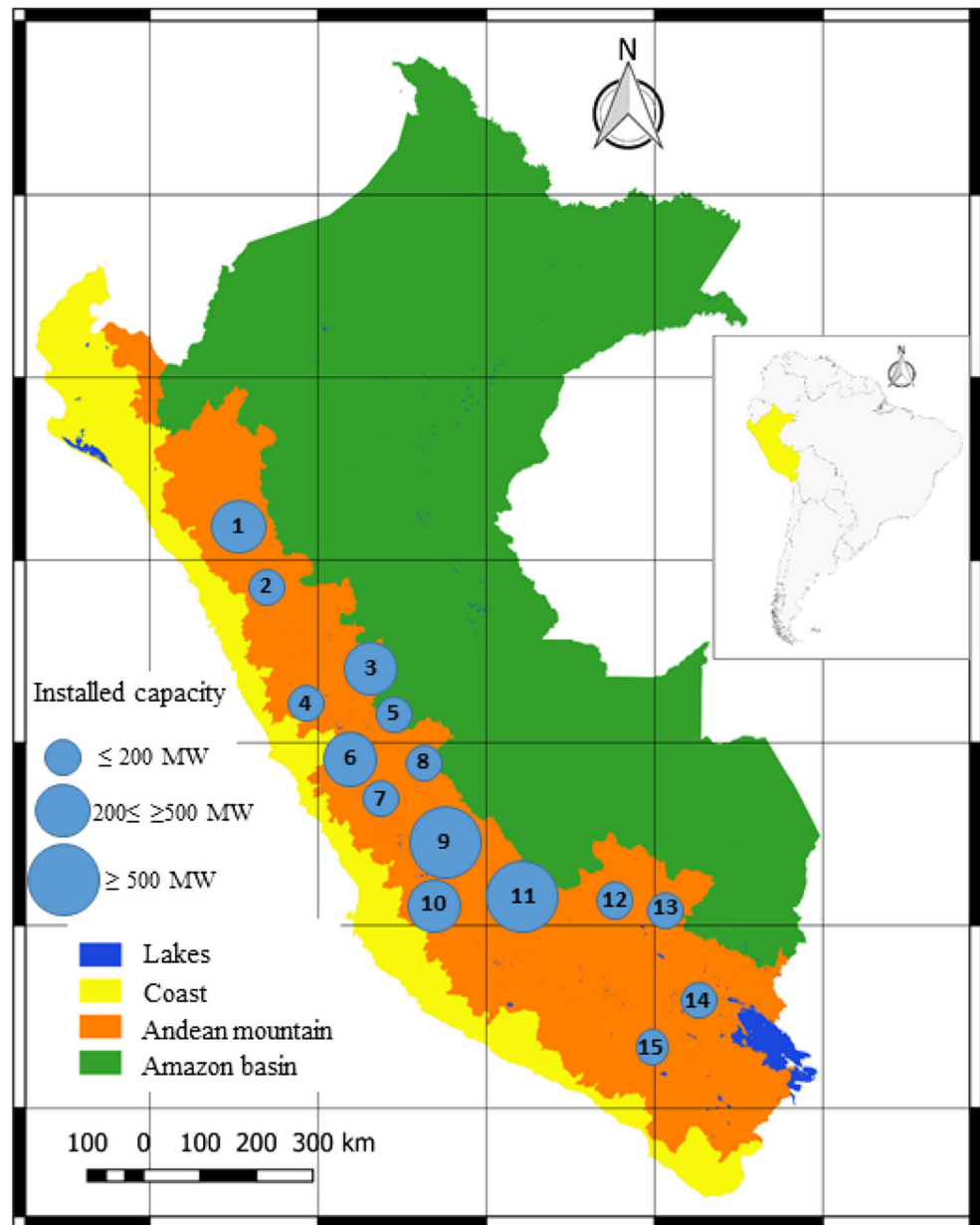
Peru is a tropical country which has relied historically on hydroelectricity for its economic growth. In fact, in the mid-1990s, approximately 80% of the electricity generated was of hydroelectric origin (MINEM 2007). Although currently

water and energy are still closely coupled, the situation started to shift considerably with the turn of the century, since the increase in installed hydropower was not fast enough to cover the sharp rise in electricity demand due to significant economic growth (Vázquez-Rowe et al. 2015). By the year 2016, the contribution of hydropower plants to the Peruvian electricity mix had fallen to 47%, with thermoelectric power plants arising, for the first time in decades, as a strong competitor to be the main source of electricity (MINEM 2007). Nevertheless, this tendency is bound to change in the next decade, since the Agency for Investment in Energy and Mining (OSINERGMIN, following its acronym in Spanish), has registered 2030 MW of new hydropower energy to be installed in the period 2017–2023, whereas no new thermoelectric power plants are planned and the investment in wind and solar energy is still low (OSINERGMIN 2017). Figure 1 shows the main hydroelectric power plants operating in Peru as of December 2016; furthermore, the technical characteristics of each one are represented in Table S1 in the Electronic supplementary material (ESM).

Considering that environmental impacts in hydropower plants are largely dependent on the specific characteristics of the plant, extrapolation of previous studies developed in other areas of the world have a limited value (Botelho et al. 2017). Therefore, efforts to understand the environmental impacts linked to hydropower plants in Peru should regain importance in order to identify specific environmental hotspots. In this context, life cycle assessment (LCA) has been a repeatedly used methodology in the scientific literature due to its holistic perspective when it comes to computing environmental burdens from a life cycle perspective (Hellweg and Milà i Canals 2014). In fact, previous studies have previously addressed the environmental profile of hydroelectric power plants using LCA. For instance, different aspects have been analyzed, such as impact evaluation for different production capacities and type of plant (Pascale et al. 2011; Flury and Frischknecht 2012) and construction and implementation impacts by miniplants (Zhang et al. 2007, 2015a, b), and a significant amount of LCA studies in the Latin-American context, most of them located in the Brazilian Amazon basin, mainly focus on large hydroelectric plants with an important amount of energy production (de Miranda Ribeiro and Da Silva 2010). Table 1 provides a summary of 10 LCA studies on hydroelectric power plants. These studies were analyzed based on a set of site-specific details, as well as technical LCA-related features, such as the functional unit utilized, the selection of environmental impact categories, and their main findings.

For the current study, a set of three hydropower plants located in the Peruvian Andes were analyzed from a life cycle perspective. The main objective of the study was to generate detailed life cycle inventories (LCIs) for each of these three hydropower plants with the aim of having specific information for real conditions in Peru. Furthermore, this information

Fig. 1 Geographical location of the main hydroelectric power plants in Peru based on installed capacity



¹Cañon del pato; ²Quitaracsá; ³Chaglla; ⁴Cheves; ⁵Yuncan; ⁶Huinco; ⁷Matucana; ⁸Chimay; ⁹Santiago Nuñez de Mayolo-Restitución; ¹⁰El Platanal; ¹¹Cerro del Águila; ¹²Machu Picchu; ¹³Santa Teresa; ¹⁴San Gaban II; ¹⁵Charcani V

was used to compute the environmental impacts linked to the generation of electricity in these plants. Although the main aim was to determine the GHG emissions linked to this process, considering the important policy implications of decarbonizing the Peruvian electricity grid, other environmental categories, such as eutrophication or the depletion of abiotic resources, including water, were also considered.

Results are intended to be of utility for an array of applications, providing a unique prospective in terms of the role of hydropower plants in climate policy. Firstly, results aim at supporting stakeholders in the development of informed

environmentally sound decisions in the energy sector in Peru and other nations in which hydropower plants are or can be installed; and secondly, in terms of policy-making at a national level, considering the implications of the energy sector in terms of meeting the nationally determined contributions (NDCs) to mitigate climate change in the frame of the Treaty of Paris (Iyer et al. 2017). Finally, data provided in the current study will be of utility for the international LCA community in an effort to expand the amount of inventories available for different geographical and technological conditions. Altogether, this allows us to cover an important

Table 1 Brief description and analysis of life cycle assessment (LCA) studies for hydropower plants in the scientific literature

Reference	Geographical location of study	Functional unit	Hydropower plant characteristics (capacity; lifespan; type)	Impact categories	Main findings
de Miranda Ribeiro and Da Silva (2010)	Brazil	1 MWh	Itaipu (12,600 MW; 100 years; reservoir)	CC, WRC, R, LU, AQ, T, O	The construction phase dominates the environmental load of the plants assessed. The main burdens identified were reservoir filling (GHG emissions; land use), the life cycle of steel (water and energy consumption; CO ₂ , particulates, and NO _x emissions), cement production (water and energy consumption), and the operation of the machinery (diesel consumption and NO _x emissions). Large hydro projects are not necessarily less environmentally favorable. These projects often perform better than smaller ones in terms of energy efficiency and GHG emissions related to the optimization of the structural design. The stages that generate the greatest impacts in a minihydropower plant are the construction and transportation phases due to the huge amount of materials required and the remoteness of the location, respectively.
Zhang et al. (2007)	China	1 kWh	44 MW; 50 years; reservoir 3600 MW; 100 years; reservoir	N/Ap	Small hydropower systems have a greater environmental impact per kilowatt hour than larger systems. Moreover, the transmission line is the dominant component in almost all LCIA impact categories. Nevertheless, it is still less carbon intensive than other sources of electricity.
Suwanit and Gheewala (2011)	Thailand	1 MWh	Nam Man 5.1 MW; 50 years; run-of-river Nam San 3.1 MW; 50 years; run-of-river Mac Pai 1 250 MW; 50 years; run-of-river Mac Thoei 2.250 MW; 50 years; run-of-river Mac Ya 1.150 MW; 50 years; run-of-river Huai Kra Thing 3 kW; 20 years; run-of-river	CC, WRC, R, AQ, T	Results suggest that dams built from local materials are more environmentally responsible than a concrete dam, mainly due to the production of cement. However, operation and maintenance generate more emissions due to the generation of biogenic GHG emissions and the maintenance of turbines and generators.
Pascale et al. (2011)	Thailand	1 kWh		CC, WRC, R, T	The results suggest that run-of-river systems consume less water in comparison with the reservoir-based plants. Evaporation during the operational phase was the major factor contributing to the water consumption.
Zhang et al. (2015a, b)	China	1 kWh	Nuozhadu Power Station 5850 MW; 33 years; reservoir-based	CC	Results suggest that an evaporative cooling system is better than the air cooling method not only in technical performance but also in environmental benefits.
Bakken et al. (2016)	Norway	1 kWh	Embreitfoss 4 50 MW; 60 years; run-of-river Trollheim 130 MW; 60 years; reservoir-based	WRC	The environmental impacts occurring throughout the life cycle of a pumped storage plant are determined by the type of electricity that is feeding the system. Wind power appears as a suitable option.
Mao et al. (2017)	China	1 kWh	Not available	CC	GHG emissions from hydropower generation are lower as compared with conventional types of electricity generation.
Torres (2011)	Norway	1 MJ stored during 1 day	Tonstad III 960 MW; 100 years; pumped storage	CC, WRC, R, LU, AQ, T	In New Zealand, tidal power is the most sustainable technology, and geothermal power is the least, especially when considering fugitive emissions.
Varun and Bhat (2010)	India	1 kWh	Bahadradad 0.25 MW; 30 years; run-of-river augmentation 1 MW; 30 years; run-of-river Badarpur 0.4 MW; 30 years; run-of-river Dhukwan 30 MW; 30 years; reservoir-based Devarabelakere 2 MW; 30 years; reservoir-based Sadani 1 MW; 30 years; reservoir-based	CC	
Rule et al. (2009)	New Zealand	1 kWh	Clyde Dam; 432 MW; 100 years; reservoir-based	CC	

N/Ap, not applicable; CC, climate change; WRC, water-related categories; R, resources; LU, land use; AQ, air quality; T, toxicity; O, other

knowledge gap when it comes to understanding the environmental profile of electricity production in emerging and developing nations, as well as to extrapolate recommendations for a wide range of countries that rely on water resources to fuel their economy.

2 Methods

2.1 Description of the case studies

The current study was developed in the frame of a wider project with the aim of developing LCIs for strategic productive sectors in Peru. The involvement of the Ministry of the Environment (i.e., MINAM) in the project allowed direct contact with many private companies. In the particular case of hydropower plants, two companies (i.e., companies A and B) finally accepted to participate in the study with data for three different hydropower plants constructed in the past decade.

Hydropower plants can be divided into three main types based on their structure and generation: firstly, impoundment plants, which are those that require vast reservoirs to store the water of the river and generate the electricity by releasing the water flow through a turbine in the lower part of the dam. These plants are common in countries such as Brazil, Spain, or the USA (Tester et al. 2012). The second type is diversion plants, commonly referred to as run-of-river (ROR) plants which channel a portion of a river through a canal or penstock. These may require the use of a dam when water flow is irregular or low (Moreira and Poole 1993; Garegnani et al. 2018). The third type is pumped storage plants which pump water uphill to a reservoir at higher elevation using other energy sources (e.g., solar, wind, and nuclear) (Egré and Milewski 2002; Tester et al. 2012; DOE 2017). In Peru, the use of ROR plants predominates compared to the other types, mainly due to the orographic characteristics which allow them to take advantage of the potential energy created by the high altitudes found in the Andes. However, future projects could be oriented to harness the hydropower potential in the Amazon basin.

Moreover, in recent years, the development of minihydropower plants has become common in Peru given the small amount of materials and land use required for their construction, operation, and maintenance. In addition, the Peruvian government has started an initiative to introduce in the electricity grid 5% of generation based on sustainable, low-carbon energy. This program, referred to by the government as renewable energy resources (RER, using the acronym in Spanish), includes hydroelectric plants with an installed capacity below 20 MW, solar plants, and wind farms (OSINERGMIN 2013).

On the one hand, company A provided data for a hydropower plant they own located in the Pacific drainage basin,

200 km northeast of the city of Lima, with an installed power capacity of 172 MW. This hydropower plant is considered a ROR generation plant, due to the fact that little water storage is provided, diverting most of the water of the two rivers it feeds off through a system of tunnels that lead to the powerhouse cavern, in which the electromechanical equipment (i.e., turbines, generators, and transformers) is installed. Thereafter, the water is returned to one of the rivers (both river flows merge after the pondage) downstream. A final small pondage is located downstream to regulate the final amount of water that is allowed to flow into the Pacific Ocean, preventing the flooding of the agricultural valleys next to the coast.

On the other hand, company B provided data for two different hydropower plants. The larger plant, located 230 km southeast of the city of Lima, in the province of Cañete, has an installed capacity of 220 MW and initiated its operation in 2010. In a similar way to the previously described plant, it is also considered a ROR plant, since it has two reservoirs used to control the amount of water stored and, thus, has a continuous water flow, even during droughts. Moreover, just like the previous plant, it diverts most of the water from the river through a system of tunnels that lead to a powerhouse cavern and, thereafter, to a small pondage downstream. A second hydropower plant belonging to the same company, with an installed capacity of 18.4 MW was also inventoried. It is categorized as a mini-ROR hydropower plant and is recognized as an RER energy project by the Peruvian government. It was inaugurated in June 2017. Therefore, no measured annual production data for the plant were available. In contrast to the previous hydropower plants, it does not have a large reservoir, since it only has a small rubber dam that diverts part of the water flow to a concrete channel and a penstock, which lead the water flow to a powerhouse downstream. Table 2 presents the main characteristics of each hydroelectric plant assessed.

2.2 Goal and scope

The main goal of the study, as mentioned above, was the generation of detailed life cycle inventory data for three hydropower plants in Peru, as well as the computation of their environmental impacts using LCA methodology. For this, the ISO 14040 guideline was applied to carry out the LCA analysis (ISO 2006). The function of the production system was the generation of electricity in three different hydropower plants located in central Peru. Therefore, the functional unit (FU), which is the mathematical relation to which the function of the system is related (Weidema et al. 2004), was set as 1 kWh of net electricity produced.

The system boundary for the three hydropower plants included the construction of the plants, operation, maintenance, and the biogenic emissions occurring in the reservoirs. Moreover, the primary transmission of the electricity from

Table 2 Description of the hydropower plants assessed in the current study

Characteristics	Hydropower plants		
	H1	H2	H3
Geographical area	Andean mountain, Lima Province	Andean mountain, Lima Province	Andean mountain, Huánuco Province
Construction year	2015	2010	2017
Installed capacity (MW)	178	220	18.4
Type of plant	Run-of-river	Run-of-river	Run-of-river
Turbines ¹	Pelton (2)	Pelton (2)	Francis (3)
Annual power production (GWh)	837	1100	147
Design flow rate (m ³ /s)	33	41	26
Height (m.a.s.l.)	668	900	2925
Water head (m)	600	625	83.5
% production over total electricity production (year 2016)	1.73	2.28	N/Av
% production over total hydroelectric production (year 2016)	3.64	4.78	N/Av

N/Av, not available

¹ Number of turbine units shown in brackets

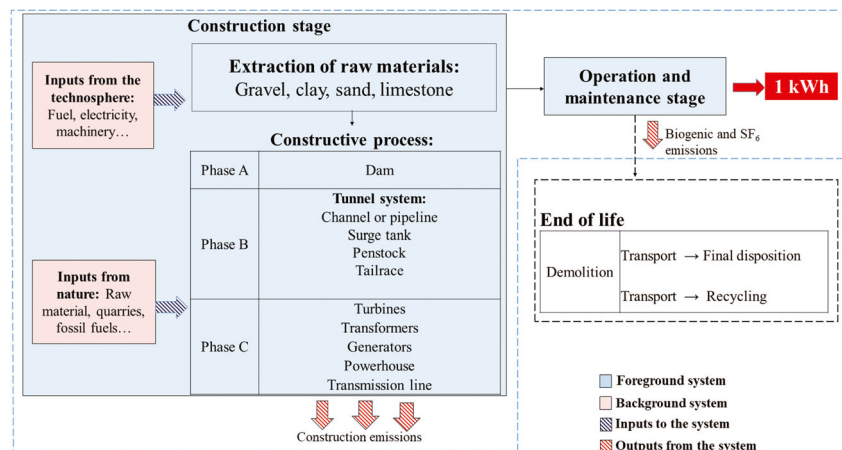
the plant up to the electrical substation was also included within the boundary (see Fig. 2). In contrast, the end-of-life (EOL), which involves the demolition and recycling of the plant, was omitted considering that the decommissioning of a large dam is rare and there is limited data in the literature for these processes. In fact, there is only information linked to demolitions and EOL for little reservoirs located in the USA due to the minimum effects downstream of the river and to the recovery of the reproduction trajectory of salmon, *Oncorhynchus* spp. (Isambert and Crepon 2004; UNEP-DDP 2006; Cho 2011).

2.3 Data collection

Primary data collection for the foreground system of the hydropower plants was conducted in several phases. Firstly, at the beginning of the project, LCA practitioners provided basic

training on life cycle thinking to participants arriving from MINAM and the companies selected for the study, allowing the participants to acquire knowledge linked to the need to collect robust, transparent, and detailed data throughout the supply chains. Secondly, the LCA practitioners developed detailed questionnaires including all the stages of hydropower electricity production (see Section S2 in the ESM) that were sent to the Corporate Environmental Responsibility Unit of the companies involved in the study. In parallel, a guided visit to the hydropower plants with technical personnel was scheduled in order to understand the specific characteristics at each site and clarify any doubts still pending. Finally, once the completed questionnaires were received and the inventories were being developed, a final round of meetings was scheduled to amend or clarify unclear data or complete missing data. The reference year for collecting data was 2016 for electricity production and maintenance operations for H1 and H2.

Fig. 2 Graphical representation of the system boundary of the production system under study



In the case of H3, however, electricity generation was not available, since its operation initiated in 2017. Therefore, the electricity generation assumed for H3 was based on the simulations undergone by the company in order to report an expected generation based on standard predicted conditions (Carlos Adrianzén, personal communication, September 2017).

Regarding secondary data for the foreground system, these were collected mainly from the scientific literature. For instance, the average lifespan of the electromechanical equipment was obtained from Flury and Frischknecht (2012). Similarly, data were retrieved from Hertwich (2013) to account for the biogenic emissions (CH₄ and CO₂) generated in the reservoirs. N₂O emissions generated in the reservoirs were modeled based on data available in ecoinvent® (ecoinvent® 2016). Secondary data for the background system were obtained mainly from the ecoinvent® v3.4 database (ecoinvent 2016), although certain inventories were adapted to Peruvian conditions, as explained in Table 3.

Data related to direct water consumption from the rivers were retrieved from internal reports provided by company B for plant H2. These data included the global amount of water that was used by the hydropower plant in the year 2016,

accounting for evaporation in reservoirs, water loss or the amount of water that was finally returned to the river through the tailrace. For the other two hydropower plants (i.e., H1 and H3), it was assumed that they require the same amount of water per unit of energy as H2.

The quality of the data sources was evaluated on the basis of five differentiated indicator scores: reliability, completeness, temporal correlation, geographical correlation, further technological correlation, and sample size for each plant (see Section S3 in the ESM for further details). These indicators were selected based on the recommendations provided by Ciroth et al. (2016) for data quality in LCIs and are in line with the quality indicators that are used by the ecoinvent® database (ecoinvent 2016). Thereafter, these quality indicators were used to generate the pedigree matrix as described in Tables S3–S5 of the ESM.

2.4 Assumptions and limitations

A series of assumptions were taken into account to build the LCI. Thereafter, these assumptions were discussed with the infrastructure area of each company for validation. Firstly, the total lifetime of the three projects was assumed to be 50 years,

Table 3 List and description of the main datasets and dataset modifications obtained from the ecoinvent® v3.4 database that was performed for the computation of the results

Dataset	Action taken
Electricity, high voltage, production mix (Peru)	The electricity grid for Peru was adapted to that of the year 2015 based on the mix reported by Vázquez-Rowe et al. (2015).
Gravel, crushed	Gravel was used for the construction of the dams and as a component of the concrete used in the construction of the dams, the system of tunnels, and the powerhouse.
Sand	Sand was used as a component of the concrete used in the construction of the dams, the system of tunnels, and the powerhouse.
Concrete, 20 MPa	Concrete was used in one of the hydropower plants for the construction of the system of tunnels. It was based on a previous study analyzing Peruvian cement and concrete production (Vázquez-Rowe et al. 2019a).
Concrete, 30–32 MPa	Concrete was used in the hydropower plants for the construction of the system of tunnels and the powerhouse. It was based on a previous study analyzing Peruvian cement and concrete production (Vázquez-Rowe et al. 2019a).
Concrete, 35 MPa	Concrete was used in the hydropower plants for the construction of the dams. It was based on a previous study analyzing Peruvian cement and concrete production (Vázquez-Rowe et al. 2019a).
Concrete, 25 MPa	Concrete was used in one of the hydropower plants for the construction of the dams, system of tunnels, and powerhouse. It was based on a previous study analyzing Peruvian cement and concrete production (Vázquez-Rowe et al. 2019a).
Transport, freight, sea, transoceanic ship	Transport of electromechanical equipment to Peru for the powerhouse. Data were aggregated, including the freight of the turbine, generator, and transformer. Distances were retrieved from Google Earth (2016).
Machinery, operation	The use of machinery for the construction and maintenance of the hydropower plants was modeled based on Peruvian conditions in terms of the lifespan of the vehicles (MTC 2003). Euro III emission standards were assumed for construction machinery.
Transport, freight, lorry 16–32 t, EURO 3	An average load factor of 5.79 t was assumed for every lorry used in the transportation of materials for each of the plants studied, following the modeling suggested by ecoinvent®.
Diesel, production	Diesel B5 is the main type of diesel used in Peru. This blend has a 5% content of sugarcane-based bioethanol, which was assumed to be of Brazilian origin.
Diesel emissions	Diesel emissions for heavy-duty vehicles used in the construction stage were modeled using the EEA/EMEP guidelines for the calculation of combustion emissions (EEA 2016).

based on the concession agreement signed between the companies and the government (M. Chávez and C. Adrianzén, personal communications, September 2017). Hence, a 50-year lifespan was estimated for the permanent structural items (e.g., dams, transmission line, etc). A shorter lifespan was considered for the electromechanical equipment used in the powerhouse: 40 years for Pelton turbines, 25 years for Francis turbines, 30 years for generators, and 30 years for transformers (Flury and Frischknecht 2012). Freight of raw materials for cement and steel was assumed to be done through road transportation in 16–32 t trucks. For the import of electromechanical equipment from Europe or Brazil, transoceanic freight ships were considered.

In the case of plant H1, the type of machinery in the construction processes, the construction process for the dam, the system of tunnels and the powerhouse for each plant, and the performance of the rock volume drilled per day in the construction of the tunnels were identified and quantified based on the layout of the hydropower plant. Moreover, the amount of materials (e.g., steel or concrete) was also calculated based on the material takeoff. For plants H2 and H3, most of the information was provided directly by the company.

Regarding the limitations, data that could not be collected due to lack of availability were completed using ecoinvent® (ecoinvent 2016). This case was presented for machinery equipment used on site (e.g., hydraulic excavator) and in the manufacture of turbines, generators, and transformers utilized in the powerhouse. In the case of explosives, no information related to the type was provided by the companies. Hence, Tovex, a water-gel explosive composed of ammonium nitrate and methylammonium nitrate, was used in the LCI modeling. The reason for this is linked to the fact that it is the only explosive available in the ecoinvent® v3.4 database. A set of emissions to air such as nitrogen oxides (including N₂O), carbon monoxide, and sulfur dioxides should be expected linked to explosive detonation. However, these were excluded from the inventory due to lack of information (NPI 2016). Nevertheless, it is foreseen that these emissions would only generate a minimal adjustment in the results presented in this study. A final limitation linked to H3 exclusively was the lack of information and, consequently, modeling of the transmission line.

2.5 Life cycle inventory

The LCI of the production system was subdivided into two subsystems (see Fig. 2). On the one hand, the construction subsystem considered the building of structural components of the plant, such as the dam, the tunnel system, the powerhouse, or the transmission line. On the other hand, the operation and maintenance was considered in terms of land use (transformation and occupation), replacement and maintenance of electromechanical equipment in the powerhouse, or

electricity consumption and loss at the powerhouse and transmission line, respectively. Fugitive emissions of sulfur hexafluoride (SF₆) due to the operation of electromechanical equipment in the transformer and generator cooling system were also included in the assessment. An emission factor of 3.40E-7 g of SF₆ per kWh due to leakage was considered based on a study presented by Vattenfall (2008), as shown in Table 4.

2.5.1 Biogenic emissions

The estimation of the biogenic GHG emissions generated by the biogenic decay in the reservoirs was done using the methodology presented by Hertwich (2013). This method makes it possible to calculate the amount of biogenic CO₂ and CH₄ emissions per unit of power generated by using a set of parameters such as energy production, land use, net primary production (NPP), and the age of the hydropower plant, as represented in Fig. 3. Firstly, data collection regarding climatic characteristics and geographical location of the reservoir was performed. Thereafter, the quantification of the NPP for each reservoir was undergone. NPP is the rate at which all the plants in an ecosystem produce net useful chemical energy (Running et al. 2000). In other words, it is equal to the difference between the rate at which the plants in an ecosystem produce useful chemical energy (GPP) and the rate at which they use some of that energy during respiration (Rosenzweig 1968). For the identification of the climate and the NPP for each of the reservoirs, information was used from the National Meteorology and Hydrology Service of Peru (SENAMHI 2017), the Köppen climate classification (Köppen 1936), and the NPP satellite information provided by the research group in charge of numerical terradynamic simulation (NTSG) at the University of Montana (UMT), using the Google Earth Engine platform (Gorelick et al. 2017). Finally, biogenic emissions were calculated using regression Eq. 1, in which the best prediction of the emission factor for CO₂ and CH₄ is provided by including the logarithms of land use and NPP as well as age as linear variable. Regression coefficients and statistics parameters are available in Table 1 of Hertwich (2013).

$$\ln E = \text{const} + B_{\text{land use}} \times (\text{land use}) + B_{\text{Age}} \times \text{Age} + B_{\text{NPP}} \times \ln(\text{NPP}) \quad (1)$$

where E represents the final estimated amount of emissions, land use refers to the total flooded area of the reservoir, age is the current lifetime of the reservoir since construction, and NPP, as aforementioned, represents the net primary productivity.

Table 4 Hydropower plant life-cycle inputs and outputs (FU = 1 kWh)

	Unit	Hydropower plants (plant total ^a)			Unit	Hydropower plants (total per FU ^b)		
		H1	H2	H3		H1	H2	H3
Inputs from the environment								
Gravel	t	8.51E+04	1.74E+05	1.94E+04	kg	2.07E-03	3.18E-03	2.63E-03
Sand	t	7.70E+04	1.49E+05	1.54E+04	kg	1.87E-03	2.72E-03	2.09E-03
Water (for construction)	m ³	2.53E+04	4.85E+04	3.17E+03	kg	6.16E-04	8.85E-04	4.30E-04
Occupation, land use	m ² a	8.46E+07	4.99E+07	3.22E+06	m ² a	2.06E-03	9.10E-04	4.37E-04
Transformation, land use	m ²	1.55E+05	3.96E+05	1.29E+05	m ²	3.77E-06	7.22E-06	1.75E-05
Water (from river)	m ³	2.73E+10	3.64E+10	4.89E+09	m ³	6.64E-01	6.64E-01	6.64E-01
Inputs from the technosphere (materials)								
Cement	t	5.61E+04	1.02E+05	7.60E+03	kg	1.36E-03	1.85E-03	1.03E-03
Diesel	t	5.67E+02	7.63E+02	2.36E+02	kg	1.38E-05	1.39E-05	3.20E-05
Explosives	t	5.38E+02	2.33E+02	1.55E+01	kg	1.31E-05	4.25E-06	2.10E-06
Steel	t	5.69E+03	9.16E+03	1.32E+03	kg	1.38E-04	1.67E-04	1.79E-04
Aluminum ^c	km	1.81E+04	1.80E+04	–	m	4.41E-04	3.29E-04	–
Polyvinylchloride (PVC)	t	5.89E+00	6.00E+00	–	kg	1.43E-07	1.09E-07	–
Aluminum ^d	t	5.43E+02	2.63E+02	2.39E+02	kg	1.32E-05	4.80E-06	3.24E-05
Iron ^c	t	1.23E+01	1.23E+01	1.41E+02	kg	3.00E-07	2.25E-07	1.91E-05
Chromium ^c	t	2.00E+00	2.67E+00	2.29E+01	kg	4.87E-08	4.87E-08	3.11E-06
Transformer	t	9.71E+02	9.70E+02	4.26E+02	kg	2.36E-05	1.77E-05	5.78E-05
Inputs from the technosphere (transport)								
Truck transport	t km	1.67E+07	2.30E+07	2.49E+06	kg km	4.10E-01	4.20E-01	3.38E-01
Transoceanic ship.	t km	1.76E+07	1.25E+07	1.02E+07	kg km	4.30E-01	2.28E-01	1.38E+00
Outputs (product and co-products)								
Hydropower plant	p	1.00E+00	1.00E+00	1.00E+00	–	–	–	–
Electricity	–	–	–	–	kWh	1.00E+00	1.00E+00	1.00E+00
Outputs (emissions to air)								
CH ₄	t	1.41E+00	2.22E+00	5.95E-01	kg	3.44E-08	4.06E-08	8.08E-08
CO ₂	t	1.50E+03	2.78E+03	1.03E+03	kg	3.64E-05	5.08E-05	1.40E-04
N ₂ O	t	1.97E+00	2.97E+00	6.89E-01	kg	4.80E-08	5.42E-08	9.36E-08
SF ₆	t	1.40E-02	1.86E-02	2.50E-03	kg	3.40E-10	3.40E-10	3.40E-10
Water	m ³	1.02E+08	1.36E+08	1.83E+07	m ³	2.49E-03	2.49E-03	2.49E-03
Outputs (emissions to water)								
Water	m ³	2.71E+10	3.62E+10	4.86E+09	m ³	6.60E-01	6.60E-01	6.60E-01

^a Total amount of materials used in the construction and operation of the plant considering a lifespan of 50 years

^b Amount of material needed per functional unit

^c Aluminum used in the construction of the transmission line

^d Aluminum used in the manufacture of the generators

^e Metals used in the process and manufacture of the turbines

2.6 Life cycle impact assessment

The computation of the environmental impacts was done in the SimaPro v8.3.0.0 software (PRè-Product Ecology Consultants 2018). Three different assessment methods were used to calculate the environmental impacts. On the one hand, the IPCC 2013 100-year method was considered to calculate the GHG emissions linked to the production systems evaluated. At the moment of the study, IPCC 2013 was the most up-

to-date and comprehensive assessment method to compute global warming potential (GWP) environmental impacts. The 100-year time horizon was selected for two reasons: (i) this horizon constitutes the most commonly used in the literature, and (ii) it represents a hierarchist perspective, the perspective of the cultural theory selected for ReCiPe 2016, as explained below.

On the other hand, a set of eight additional impact categories were computed using the ReCiPe 2016 method. The

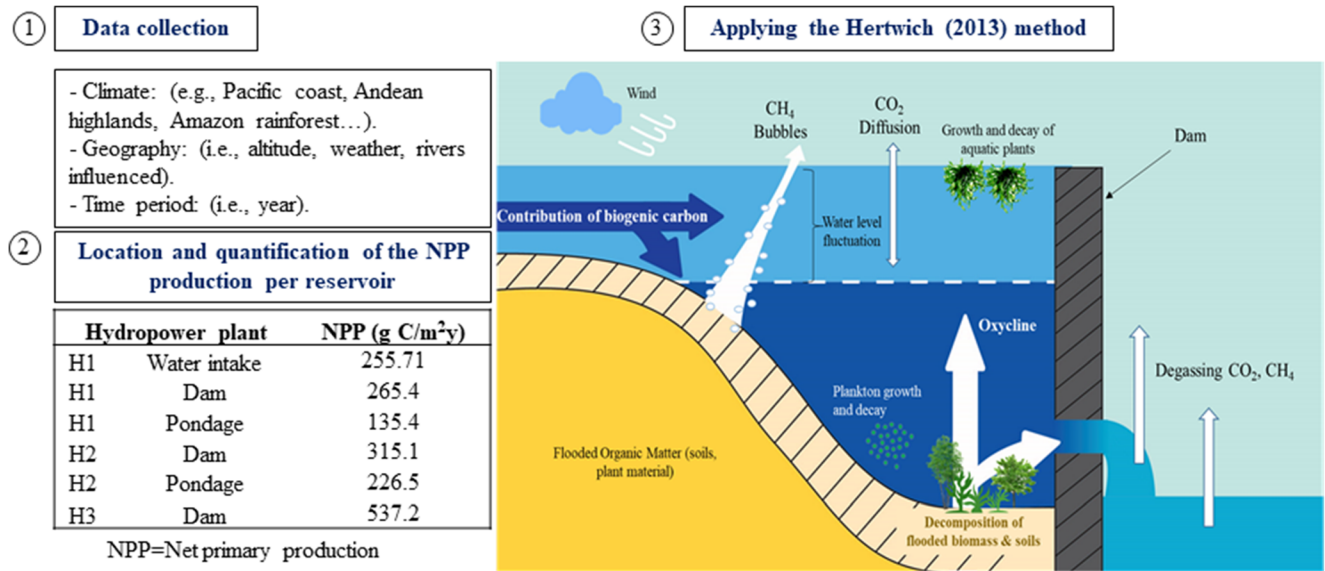


Fig. 3 Procedure to quantify the biogenic emissions generated in the reservoirs of the hydropower plants using the method developed by Hertwich (2013)

selection of this updated version of ReCiPe rather than the use of ReCiPe 2008 was performed based on a series of improvements in many of the impact categories included in the method. Firstly, ReCiPe 2016 provides characterization factors for the global scale rather than for European conditions, which implies a more accurate approximation of the potential impacts in the context of Peru and Latin America (ReCiPe 2016). In particular, this observation is of special interest for fine particulate matter formation (FPMF), which substitutes the former particulate matter formation category, photochemical ozone formation (POF), freshwater eutrophication (FE), and terrestrial acidification (TA). Secondly, stratospheric ozone depletion (SOD) now includes a specific characterization factor for nitrous oxide (N₂O), which is an important air emission in hydropower plants.

Toxicity-related impact categories and ionizing radiation were excluded from the assessment. For the former, no data linked to the degradation of water quality in the tunnel system were available. Considering that this degradation is linked to heavy metals, these were not included (Flury and Frischknecht 2012). For the latter, the main anthropogenic emissions that cause this impact (i.e., nuclear fuel cycle, coal burning, and extraction of phosphate rock) were not considered relevant based on the inventory modeled in the current study.

Finally, regarding water consumption impacts, the AWARE method was selected to report the results since it is considered a sophisticated measure of water removal from the ecosphere (Boulay et al. 2015; WULCA 2016). Characterization factors at a subwatershed level were used to calculate water consumption impacts, as shown in Table S6 in the ESM. Furthermore, the watershed selected for each plant corresponded to the location of the reservoir.

2.7 Scenario and uncertainty analysis modeling

For this study, a scenario analysis was developed in order to determine how changes in variability and uncertainty parameters in the production system may influence the final results. Considering that the general scenario modeled for the hydropower plants will be referred to as the baseline scenario (A0), three different sets of alternative scenarios were created. Firstly, scenarios A1 and A2 were modeled to account for a modification in the annual electricity generation due to the ongoing deglaciation in the Andean mountains, since this phenomenon directly affects the amount of water in the regional hydrological cycle (Barnett et al. 2005; Gloor et al. 2013). Consequently, based on the data available in Bradley et al. (2006) and Vergara et al. (2007), scenario A1 considered a 50% reduction of the glacier area in the Peruvian Andes, whereas scenario A2 represents a pessimistic scenario in which 100% of the glacial area would disappear.

A second set of scenarios focus on the modification of the useful life for each hydropower plant. These scenarios were based on the rationale that concession agreements between the government and each company tend to be extended once the 50-year period is over (OSINERGMIN 2016). Hence, scenario B1 assumed a total lifespan of 100 years for the hydropower plants, whereas scenario B2 assumed a 120-year period. Finally, a third scenario (C1) took into consideration the variation in the amount of biogenic emissions generated in the reservoirs by modifying the statistical parameters (i.e., potential net primary production, age, or land use) reported by Hertwich (2013). Subsequently, the study was expanded to an additional 14 hydropower plants in Peru, for which biogenic emissions in their reservoirs were computed based on Eq. 1,

in order to identify the variability and importance of these types of emissions throughout the sector. H1 and H2, together with these 14 hydropower plants, represent the entire sector for plants above 100 MW of installed capacity. The plants included in this scenario represent 37% of the total electricity generation in Peru in the year 2016 (COES-SINAC 2016).

Uncertainty was calculated for GWP using a Monte Carlo (MC) simulation. MC uses repeated random sampling to generate simulated data to use with a mathematical model, allowing a computation of product results while accounting for variability in the inventory values. In this case, the procedure consisted in generating pseudo-random values (1000 iterations) for each data point, following their probability distribution calculated with the pedigree matrix (Weidema 1998). The pedigree matrix quantifies the quality of the information taking into account indicators of reliability, integrity, temporal correlation, geographic correlation, technological correlation, and sample size (Ciroth et al. 2016). Approximately 75% of process units available in the ecoinvent® include a lognormal distribution calculated with the pedigree matrix, whereas most of the remaining units lack any type of distribution. Moreover, the distribution for the unit processes generated in the current study (see Table 4) was generated using geometric standard deviation given the low number of samples used (i.e., three hydropower plants).

3 Results

3.1 Global warming potential environmental impacts

Results obtained in terms of GHG emissions for the three hydropower plants per FU range from 2.06 g CO₂eq (H1) to 2.42 g CO₂eq (H2). The minihydropower plant (H3) presented an intermediate value of 2.33 g CO₂eq. However, if the total annual emission of each plant is considered, substantial differences can be identified, mainly attributable to the differing installed capacity and, therefore, size of the plants. In this sense, H3 showed the lowest value of 17,156 t CO₂eq per year, H1 presented an annual emission of 84,600 t CO₂eq, and in the case of H2, this number rose to 125,519 t CO₂eq.

Despite the similarity in terms of total GHG emissions per FU, when the distribution of these emissions is analyzed, certain differences can be observed between plants. In this sense, H1 and H2, which have a similar structure, show only slight differences in environmental impact. For instance, impacts in H1 were higher in terms of water intake (10.2%), as compared to H2 (2.8%), whereas in the case of the pondage, the more intensive use of materials in H2 represented 14% of total impacts (7% for H1). For the remaining activities included in the assessment, the differences between the two plants were minimal, with the dam, the powerhouse, and the tunnel system accounting for two thirds of total GHG emissions (see Fig. 4).

In the case of the transmission line, the impacts were higher per FU for H1 than for H2. However, when analyzed for the entire hydropower plants, it is observed that the length of the transmission line in H1 (100.8 km) and in H2 (100 km) is almost identical, and differences are only attributable to the difference in electricity production between the two plants. Finally, in the case of biogenic and SF₆ emissions, in both cases, the overall relative contribution was ca. 6%.

Plant H3, in contrast, shows a higher contribution linked to biogenic and SF₆ emissions both in relative terms (10.6%) and in absolute value (247 mg CO₂eq/FU). The powerhouse accounts for 46% of the total impact, due to a less intensive use of materials in terms of dams and other structural elements, on the one hand, and to the use of Francis rather than Pelton turbines, which are substantially heavier, on the other.

Figure 5 presents the same emissions generated in each hydropower plant, but disaggregated per material and energy sources used in the construction and operation. The results show that the production of concrete represents the largest portion of total GHG emissions in all the hydropower plants, ranging from 37% in H3 to 58% in H2. More specifically, the raw materials used to produce cement, as well as the energy used in its manufacture, account for most of this impact. The utilization of reinforcing steel, which is intimately related to the use of concrete in most construction processes included in a hydropower plant, represented 12–15% of total impacts. Electromechanical equipment (i.e., transformers, turbines, generators, etc) represented a substantial amount of environmental impact, primarily linked to the high amounts of cast iron and chromium used in their manufacture. Despite the fact that these elements were imported from Europe, GHG emissions due to marine freight were negligible. Regarding SF₆ emissions, these remained constant across the three plants. However, it should be noted that the assigned fugitive emissions linked to SF₆ leakage were obtained from the bibliography per FU. Finally, regarding biogenic emissions, H3 presents a threefold increase in relative contribution as compared to H1 and H2, mainly due to the higher concentrations of NPP in the adjacent areas of the inundated zones.

3.2 Water-related environmental impacts

When using the AWARE assessment method, the results regarding consumptive water use demonstrated that the larger amount of water was related to the evaporation occurring in the reservoirs analyzed in this study. Nevertheless, the results vary substantially depending on the characterization factors assumed for water evaporation in these reservoirs. For instance, considering that the lack of data implied that the same amount was assumed for each hydropower plant in terms of water per kilowatt hour produced, when the mean Peruvian characterization factor for AWARE is applied, the results are the same for the three plants (i.e., 63 L/kWh). However, when

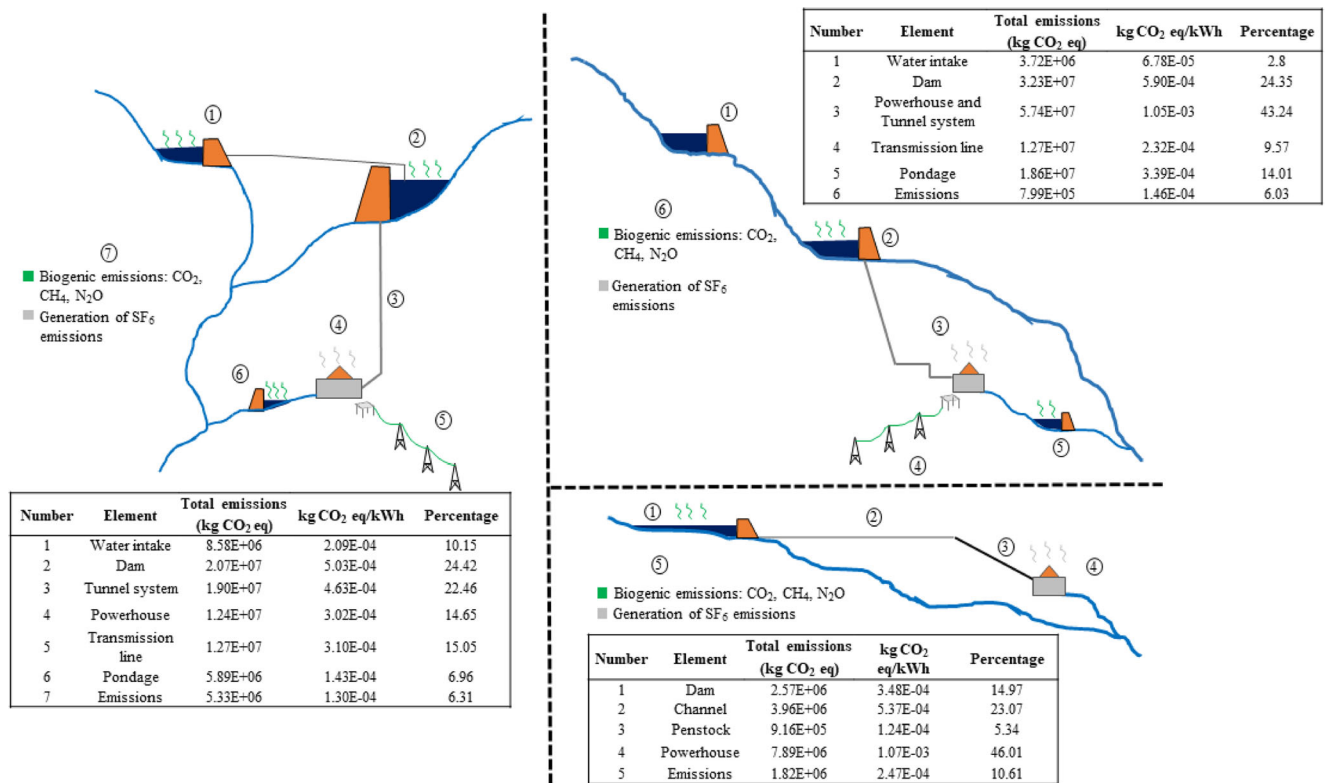


Fig. 4 Graphical representation of the distribution of GHG emissions generated in the hydropower plants assessed per structural item

local characterization factors are used, the impact on water consumption is lowest for H3, in the Amazon basin (1.3 L/kWh), whereas the results for H1 (4.6 L/kWh) and H2 (4.3 L/kWh) are somewhat higher. Table S6 in the ESM provides

further details regarding the effect of different characterization factors on these results.

Regarding degradative water use, the freshwater eutrophication impact category shows that in all three plants the

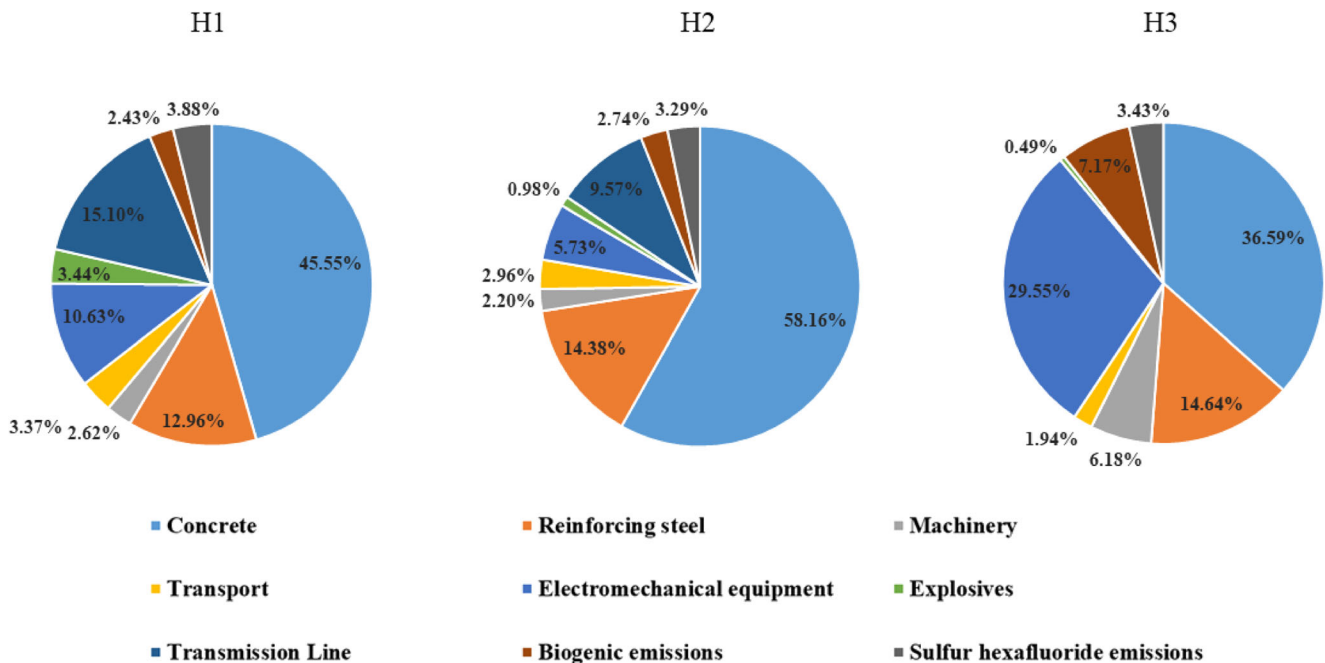


Fig. 5 Graphical representation of the distribution of GHG emissions generated in the hydropower plants assessed per materials and energy sources and emissions

environmental impacts are dominated by the production processes linked to concrete, steel, and cast iron (see Fig. 6).

3.3 Other environmental impact categories

The results obtained for the remaining impact categories can be observed in Fig. 7 for H1 and in Figs. S1–S5 and Tables S7–S12 in the ESM. Although certain differences apply for the three hydropower plants, most of these are linked to the intensity of resource and energy use in the construction of the plants and to a lesser extent to the length of the transmission line and the biogenic emissions.

For the SOD impact category, it should be noted that ReCiPe 2016 includes the characterization of N₂O, the single most ozone-depleting substance in the twenty-first century thanks to the reduction of chlorofluorocarbons (CFCs) (Ravishankara et al. 2009). This substance, which is not included as ozone-depleting in previous life cycle assessment methods, represented over 75% of the total impact in H1 (ReCiPe 2016). More specifically, N₂O emissions generated in the production of the explosives (i.e., Tovex) were responsible for over 50% of total impacts. These emissions are linked to the use of calcium and ammonium nitrate in the production of Tovex. Moreover, biogenic N₂O emissions accounted for approximately 20% of total impacts in SOD. In terms of FPMF, impacts were dominated almost entirely by sulfur dioxide (54%) and PM2.5 (46%) related mainly to the use of machinery in the construction process. However, it is important to take into consideration, as abovementioned, that particulate matter generated due to the detonation of the explosions

was not included within the system boundaries. Regarding ozone formation in the troposphere, NO_x linked to freighting, concrete production, and the assemblage of metallic components of the plants represented over 85% of total burdens.

3.4 Uncertainty and scenario analysis results

The scenario analysis results show that considerable variations in GHG emissions can be attained if the effect of dwindling glaciers in the Peruvian Andes is taken into consideration. In this sense, the environmental impacts of plant H1 would increase by 10 and 16% if the glacial surface is reduced in the next decades by 50 and 100%, respectively (see Fig. 8 and Figs. S6–S7 in the ESM for results for H2 and H3). These results are related to the reduction of water column that directly affects electricity production since it depends on the amount of water available in the reservoir. In contrast, the scenarios modeled related to the lifespan, that is B1 and B2, would present a significant reduction of GHG emissions, 43 and 50%, respectively.

Scenario C1 shows the uncertainty in the estimation of the biogenic emissions in H1 and H2, as well as a group of 14 additional hydropower plants. When analyzing the mean regression coefficients, the results for H1 and H2 show that biogenic GHG emissions are below the average worldwide values reported by Hertwich (2013). Moreover, if the upper boundary is considered, most of the plants analyzed in Peru (see Fig. 9), including H1 and H2, would still show substantially lower emissions than the worldwide average (i.e., 161 g CO₂eq/kWh).

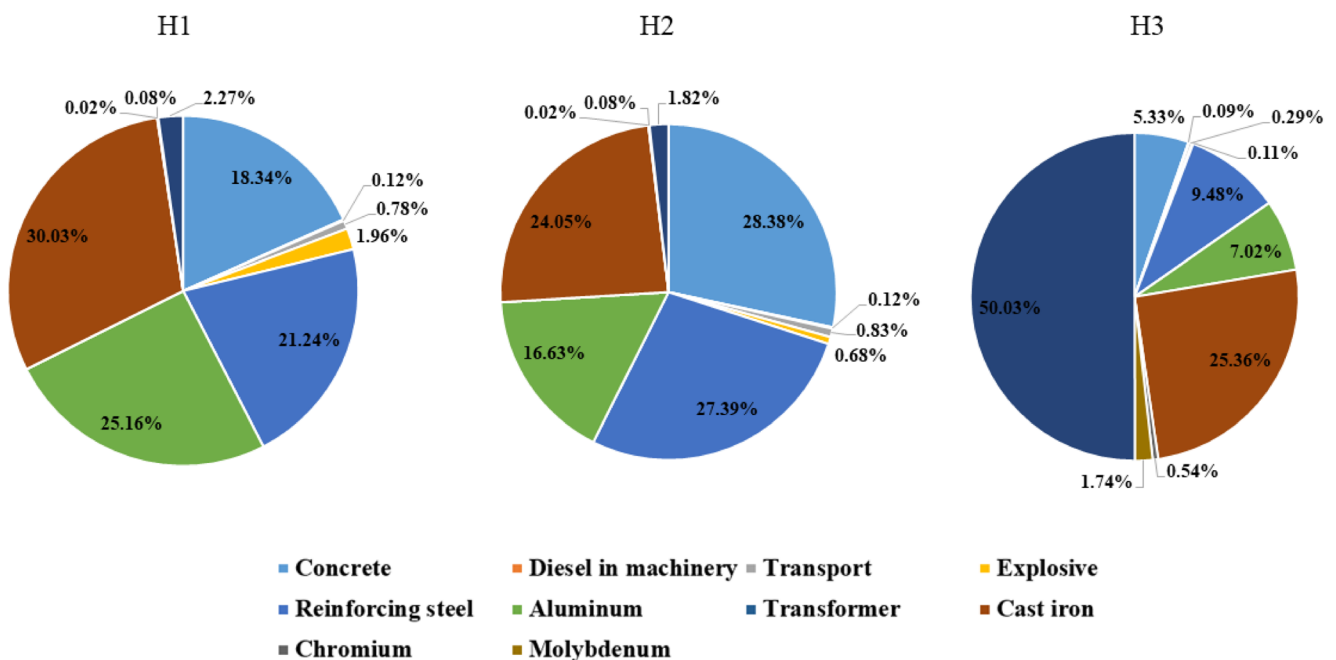
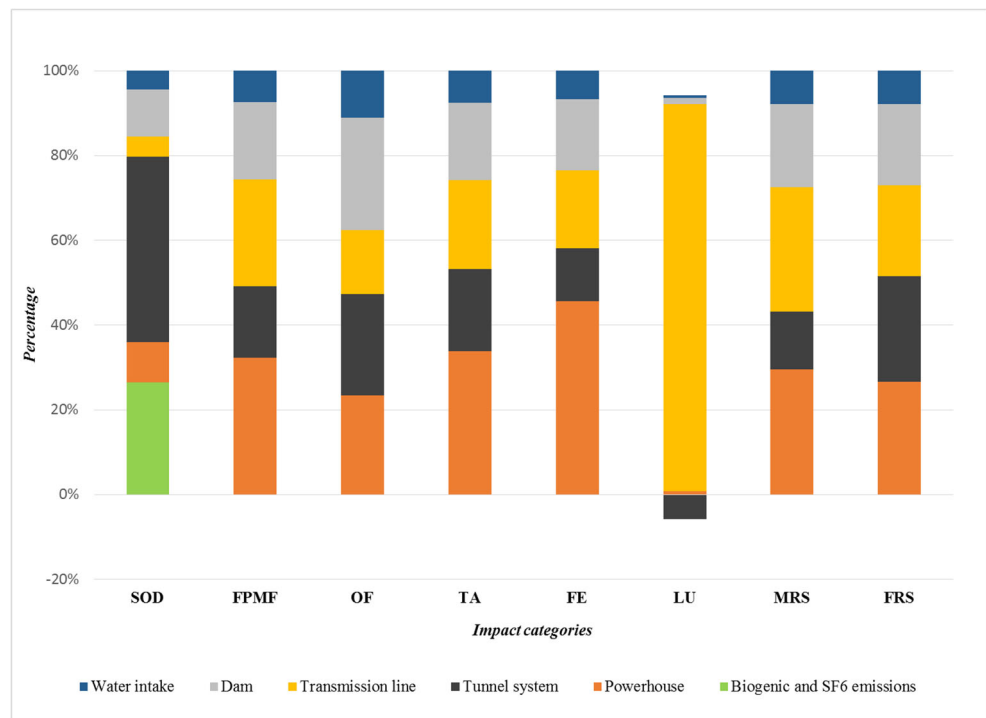


Fig. 6 Graphical representation of the distribution of eutrophying emissions generated in the hydropower plants assessed per materials and energy sources and emissions

Fig. 7 Relative environmental impacts in hydropower plant H1 per structural item for selected impact categories using the ReCiPe midpoint-H 2016 methodology. Note: SOD, stratospheric ozone depletion; FPMF, fine particulate matter formation; OF, ozone formation; TA, terrestrial acidification; FE, freshwater eutrophication; LU, land use; MRS, mineral resources scarcity; FRS, fossil resources scarcity



The individual MC simulations for each plant were computed in order to account for the sensitivity of the results obtained considering the variability of input parameters. As shown in Table S13 in the ESM, no peculiarities in the dispersion of the results were identified.

4 Discussion

4.1 Environmental hotspots and mitigation actions

The GHG emissions per kilowatt hour estimated for the three plants assessed in the study are in the lower range of emissions

observed in the literature for hydropower energy sources (Amponsah et al. 2014), which range from 2 g CO₂eq/kWh to 75 CO₂eq/kWh. In this sense, the main carriers of these positive results are installed capacity, the preponderance of construction activities rather than biogenic emissions in the overall impact, the “power tower” characteristics of the Peruvian Andes in terms of natural potential energy, and the fact that these plants were built recently with relatively new technology. Unlike in other tropical areas of the world, the orographic and climatic conditions of Peru allow important amounts of hydroelectric power to be generated at a low biogenic emission cost, thanks to the lack of vegetation and heavy organic matter loads in the Andean highlands (Asner

Fig. 8 Scenario analysis of GHG emissions in hydropower plant H1. Data reported per functional unit: 1 kWh of energy produced. Scenario A0 = baseline scenario; A1 = 50% reduction of the glacier area in the Peruvian Andes; A2 = 100% reduction of the glacier area in the Peruvian Andes; B1 = extended lifespan of 100 years for the plants; B2 = extended lifespan of 120 years for the plants

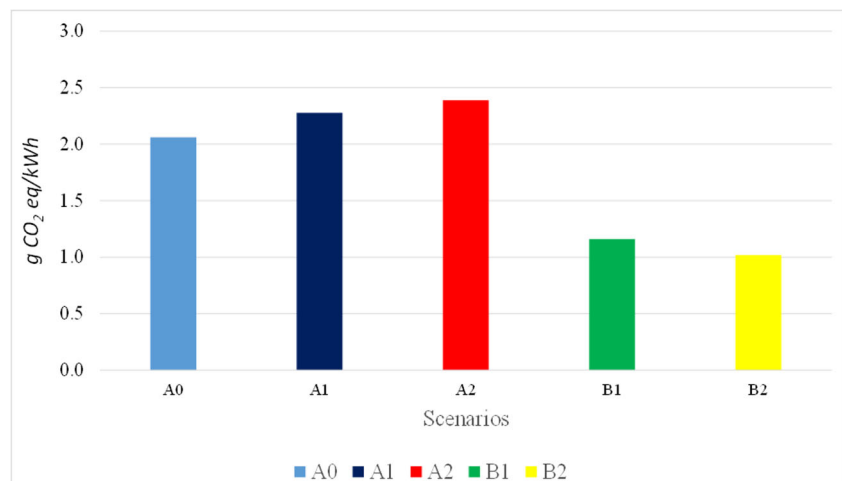
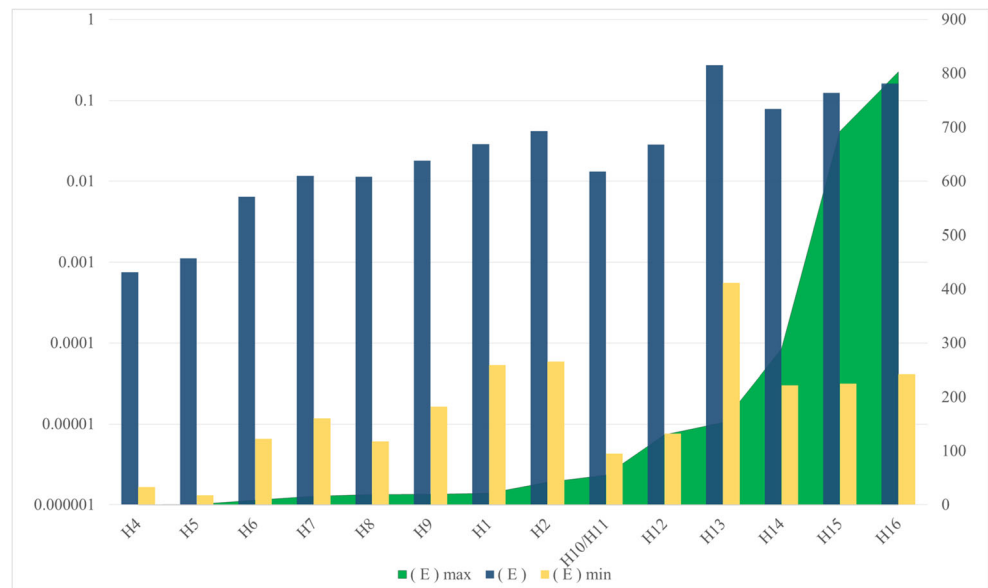


Fig. 9 Biogenic emissions represented in gram CO₂eq per kilowatt hour in the main existing hydropower plants (> 100 MW) in Peru in 2016. The right Y-axis represents the GHG emissions considering the maximum coefficient values related to NPP, land use, and age of the reservoir, as described by Hertwich (2013). The left Y-axis represents logarithmically the GHG emissions for the average and minimum coefficient values



et al. 2014). However, this would not be the case if hydropower plant projects start to spring in the low Amazon basin.

In the case of minihydropower plants evaluated (2.3 g CO₂eq/kWh), when compared to the results in the literature, most of which are located in Asia, these show a range from 11 to 53 g CO₂eq/kWh (Zhang et al. 2007; Pascale et al. 2011; Suwanit and Gheewala 2011). Nevertheless, it should be noted that in these studies, the transmission line—an item that was excluded in H3 due to data availability—was an important contributor to GHG emissions. In contrast, a recent study by Briones-Hidrovo et al. (2017) in a 21-MW plant in Ecuador suggests a similar value of 2.6 g CO₂eq/kWh.

The overall low-carbon results obtained for the three plants present a set of environmental hotspots. Although many of the mitigation actions that could be promoted would be difficult to implement in plants that are already constructed and in operation, these recommendations could be useful for the new plants that will be constructed in the near future (Pinho et al. 2007). For instance, GHG emissions linked to concrete production, which are highly intensive in these types of infrastructure, vary substantially depending on the clinker to cement ratio used in the production of cement. More specifically, when pozzolans are used in the production process, the ratio of clinker to cement is reduced to around 0.6 and GHG emissions could be reduced by approximately 25% (Huntzinger and Eatmon 2009; Vázquez-Rowe et al. 2019).

In terms of water consumption using the AWARE method, results show that the hydropower plants assessed are located in areas with medium–low characterization factors, in which the competition for water is not critical. Having said this, deglaciation modeled in the scenario analysis for GHG emissions would also imply a revision of the characterization factors in the Andes, resulting in a likely increase in the factors in

the dry season (i.e., April to November) due to modified seasonality in the energy–water nexus (Gaudard et al. 2018). In terms of eutrophication potential, most of the impacts, as shown in Fig. 6, are linked to construction and maintenance activities. Based on the information provided by the companies, no algal blooms were reported in the reservoirs, an observation which fits in with the low organic matter that they receive. However, on-site eutrophication may constitute an important source of emissions in plants located in tropical areas (Anderson et al. 2018).

With respect to the generation of biogenic emissions, a possible step forward could be the inclusion of NPP monitoring and potential biogenic emission estimation in environmental impact assessment (EIA) studies for future hydroelectric projects in Peru. Aggregating this specific computation in EIA studies would provide a prospective analysis of the impact of biogenic emissions, which could not only strengthen the technical and scientific robustness of EIA for hydropower plants in Peru but also aid in the characterization of project alternatives in areas with lower intensity regarding the degradation of organic matter (Pinho et al. 2007; Hertwich 2013; Erlewein 2013).

Finally, biogenic emissions linked to the installation of the transmission line were negligible in the plants evaluated due to the arid conditions of these zones, despite the high land use potential that has been allocated to this infrastructure. The rationale behind this high land occupation ratio allocated to the transmission line is linked to the unavailability of this land for other uses, although in some cases it could be argued that part of this land may be inaccessible. Nevertheless, in a different altitudinal and/or climatic context, for instance, tropical rainforest, the impact of the transmission line on land use

change, GHG emissions, and loss of biodiversity should be analyzed in detail.

4.2 Policy support

Energy production constitutes one of the most critical pillars of the Peruvian road to meeting the GHG emission mitigation targets established in the Treaty of Paris. In fact, the Peruvian government intends to reduce its GHG emissions linked to the energy sector (excluding transport) by 10.7 Mt CO₂eq as compared to the business-as-usual (BAU) estimate in 2030, 12% of total reduction targets collected in the Peruvian NDCs (Gobierno del Perú 2015). According to the latest revision of the NDCs, 2.1 Mt CO₂eq would be attributable to increasing the participation of hydropower in the electricity mix to 55%, as well as a 5% contribution of RER energy. Consequently, the maintenance of existing plants and the construction of new hydropower plants constitute an important way in which Peru can attain its climate mitigation targets.

The three hydropower plants assessed in the current study attain very low emissions per unit of energy produced (see Fig. 4). Moreover, when Fig. 10 is observed, it is evident that most existing hydropower plants are located in relatively high Andean areas, where the amount of above- and belowground carbon is either extremely or relatively low (Asner et al. 2014). This allows us to state that regardless of the lifetime, material use intensity, or capacity factors of the plants, which will affect the anthropogenic GHG emissions, biogenic emissions in most of the reservoirs of the plants currently operating are relatively low (see Fig. 9).

However, when the geographical locations of plants that are currently under tendering or construction are analyzed, a tendency to construct these infrastructures toward the Amazon rainforest can be observed. In this sense, the six new projects that are represented with a yellow triangle in Fig. 8, two of which would be reservoir-type plants, are located in areas with substantially higher levels of carbon storage than existing projects. These higher carbon storage levels, which translate into higher levels of NPP, imply that the aerobic and anaerobic emissions linked to the degradation of organic matter will be higher than those of the average hydropower system already in existence. Moreover, it should be noted that the larger portion of biogenic emissions in reservoirs occurs in the first few years of operation after construction (Barros et al. 2011). Considering that these new plants are intended to be inaugurated in the period 2018–2023, it is plausible to assume that most biogenic emissions at these plants will be generated before the predicted mid-century peak in radiative forcing (Meinshausen et al. 2009).

In this respect, it should be noted that the Peruvian government does not consider in an increase in these biogenic emissions for its 2030 BAU scenario (Gobierno del Perú 2015). Hence, we hypothesize that the NDCs for the electricity mix in

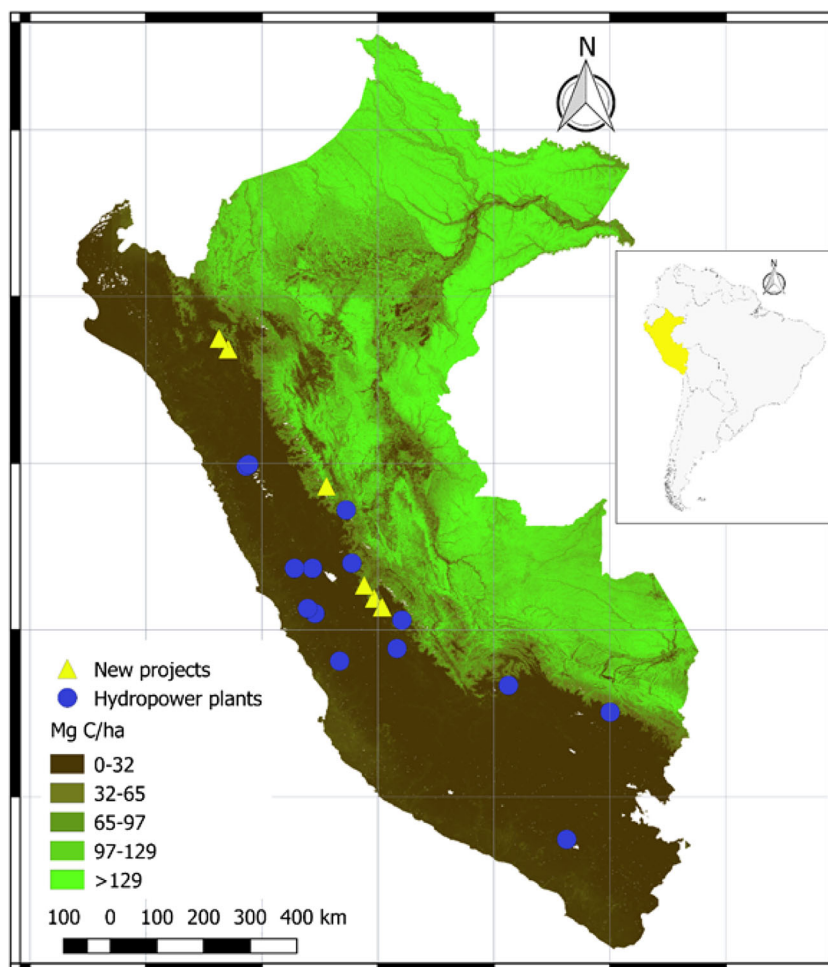
Peru should be revised in order to account for these emissions that will alter the carbon intensity generated by new hydropower plants in tropical areas, unless the national policy to expand the hydropower sector restrains from building new plants in these areas (Vázquez-Rowe et al. 2019b).

Nevertheless, it should be noted that an important portion of the Peruvian Amazon has an electricity grid that is not interconnected to the rest of the nation, in which burning diesel for electricity generation is the main source of energy (MINEM 2016). For instance, the region of Loreto, the largest in Peru, has an isolated electricity grid system that is powered entirely with thermoelectric power (MINEM 2007). In this sense, expanding the frontier of hydropower plants to the Amazon area of Peru may be an opportunity to interconnect and deliver electricity to isolated areas of the Amazon basin. However, we argue that decentralized RER systems such as wind and solar energy may be a more efficient method to deliver low-carbon energy to remote Amazonian areas due to the minimization of land use changes (e.g., flooding or transmission lines) and the avoidance of biogenic GHG emissions in high-carbon storage land (Bekele and Tadesse 2012; Bazán et al. 2018). In this sense, the development of pumped storage plants in Peru, currently nonexistent, may also offer important advantages in terms of load balancing the electricity grid, taking advantage of off-peak production and, ultimately, supporting low-carbon emission electricity use (Zhang et al. 2015a, b). However, a recent study by Song et al. (2018) suggests that pumped storage plants may present substantially higher GHG emissions, comparable to those of fossil fuels.

The location of the new projected hydropower plants encompasses a range of habitats from high Andean grasslands to lowland rainforests. Consequently, regardless of GHG emissions, hydropower plants located in these areas will also generate environmental impacts in terms of biodiversity loss (Dorber et al. 2018). Moreover, social consensus and the impact on social communities is an important issue to consider in Peru, since hydropower has traditionally engendered more social opposition than other energy projects (e.g., thermoelectric plants) (Wilbanks and Kates 2010; Vázquez-Rowe et al. 2015). In addition, a series of studies have delved into the appropriateness of developing small-scale hydropower projects or whether it is more environmentally friendly to develop large localized projects. Although the general perception is that hydropower should shift toward small projects, Erlewein (2013) suggests that this is not always necessarily true since this would translate into the disappearance of long river stretches, fragmenting tributary networks and threatening biodiversity and the sedimentation cycles in the Amazon basin (Anderson et al. 2018).

These three aforementioned issues constitute important pillars of the sustainability of hydropower projects and cannot be easily responded to through LCA alone due to the inherent limitations of the methodology in terms of covering social

Fig. 10 Geographical location of the main existing (blue dot) and projected (yellow triangle) hydropower plants in Peru



issues or the complexity of evaluating biodiversity loss. However, we argue that LCA should be considered a key environmental management methodology to provide support in future hydropower projects in Peru, since it will shed light on site-specific climate change mitigation potentials, as well as on an array of additional impact categories, such as use of resources, air quality impacts, or degradation of water resources.

5 Conclusions

The energy sector is forecasted to continue its atomization process, reducing reliance on fossil fuels while augmenting the variety of sources that power anthropogenic activities. Hence, water resources are expected to continue to have a relevant role in providing electricity in many nations given the low-carbon emissions they usually imply. Peru has historically used water resources to quench its thirst for energy. High economic growth in the early years of the century, however, triggered the development of thermoelectric power to account for the additional energy demand. Newly constructed

hydropower plants in the 2010s have allowed Peru to maintain hydropower energy as the main source of electricity in recent years. Three of these recent plants, most of which are ROR systems with small reservoirs built in relatively arid areas of the Peruvian Andes, were inventoried and analyzed in the current study using LCA. The results for these plants demonstrate that Peru has been capable of supplying new hydropower energy in the past decade with very low GHG emissions per unit of energy generated, to a great extent thanks to low biogenic emission generation. Although extending their lifetime beyond 50 years could further reduce the GHG emissions, rapid deglaciation in the Peruvian Andes could counterbalance this tendency while increasing water scarcity.

In contrast, when observing the projected new hydropower plants for the next few years, most of these will be located at lower altitudes in the Amazon basin. Some are even designed to be reservoir plants, in which the flooded area is usually considerably more intensive than in ROR plants. Therefore, we hypothesize that biogenic emissions linked to electricity generation in these new infrastructures could be significantly higher than for those observed in this study. In this context, it is recommended that the Peruvian authorities introduce

prospective mechanisms to account for biogenic emissions linked to site-specific conditions in order to support the national policy to mitigate climate change (NDCs). An option worth exploring would be the introduction of biogenic emission estimations in EIA studies of hydropower plants to strengthen the technical robustness of this management tool. This strategy would allow decision-makers worldwide to assess the feasibility of producing low-carbon energy through hydropower based on site-specific conditions.

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