



# Hydropower and environmental sustainability: A holistic assessment using multiple biophysical indicators

Andrei Briones-Hidrovo<sup>a,b,\*</sup>, Javier Uche<sup>a</sup>, Amaya Martínez-Gracia<sup>a</sup>

<sup>a</sup> Research Centre for Energy Resources and Consumption (CIRCE), University of Zaragoza, Campus Río Ebro, Mariano Esquillor Gómez, 15, 50018 Zaragoza, Spain

<sup>b</sup> Institute for Applied Sustainability Research (iasur), Av. Granados E13-55 e Isla Marchena, No. 44, 170503 Quito, Ecuador

## ARTICLE INFO

### Keywords:

Hydropower  
Low-carbon combustion-free energy  
Indicators  
Environmental sustainability  
Biophysical assessment

## ABSTRACT

Along with other low-carbon combustion-free energy sources, hydropower is considered a valuable tool for mitigating the current climate and ecological crisis and achieve environmental sustainability. However, it is still unclear to what extent hydropower is or not environmentally sustainable. The literature reveals i) that no truly holistic assessments have been carried out and ii) that there are contradictory results and conclusions. The present study addresses this gap by conducting a holistic assessment, using eight biophysical indicators of different approaches, and taking two different hydropower plant schemes as study cases. The results of the assessment show that the run-of-river hydropower plant study case is by far more environmentally sustainable than the dam hydropower plant scheme. As hydropower schemes and sizes vary, it is highlighted the importance of including as many indicators as possible to ensure broader and complete assessments and the avoidance of bias in the conclusions and ease comparison with other low-carbon combustion-free energy sources and their technologies. Moreover, the present study addresses how and within which parameters the environmental sustainability of hydropower is usually determined. The complementary set of indicators provided here, which have different scope and complexity, could be adopted for improving future decision-making in energy policies and specifically for hydropower.

## 1. Introduction

### 1.1. Hydropower and environmental sustainability

The world needs to increase the production of low-carbon combustion-free (LCCF) energy<sup>1</sup> to phase out fossil fuels, fight climate change, keep global warming below 2 °C, protect ecosystems, and achieve environmental sustainability. This is framed within the current sustainable development goals adopted by the United Nations agenda and supported by the Intergovernmental Panel on Climate Change (IPCC, 2018; United Nations, 2019). The use of LCCF energy sources has grown steadily from the beginning of the 21st century onwards (Ritchie, 2017). Currently, they account for 11% of the total final energy consumption, of which hydropower accounts for 33% (REN21, 2020). In this context, environmental sustainability (ENSU) of LCCF energy systems needs to be assessed, particularly hydropower, which closely interacts with terrestrial and aquatic ecosystems and demands-resources of different natures.

A wide range of studies have addressed the environmental and ecological impact of hydropower from different approaches and using different methodologies and methods (e.g. Barros et al., 2011; Briones-Hidrovo et al., 2019; Pang et al., 2015a, 2015b; Dias Coelho et al., 2017). This has undoubtedly contributed to a better understanding of the performance of this LCCF energy system in environmental terms.

However, few studies have aimed to precisely determine the ENSU of hydropower (Chen et al., 2020; Kumar and Katoch, 2016; Varun et al., 2010). A single approach was followed in some cases, being environmental accounting through energy assessment applied (Ali et al., 2020; Chen et al., 2020; Tassinari et al., 2016). According to the literature reviewed, however, most other studies focused on the global sustainability assessment (social, economic, and environmental dimensions) of electricity generation technologies, including hydropower. In these cases, life-cycle assessment was found to be the most common approach applied to assess the environmental side, where CML 2001 and ReCiPe 2016 methods were applied (Akber et al., 2017; Gaete-Morales et al.,

\* Corresponding author at: Research Centre for Energy Resources and Consumption (CIRCE), University of Zaragoza, Campus Río Ebro, Mariano Esquillor Gómez, 15, 50018 Zaragoza, Spain.

E-mail address: [andreicbh86@gmail.com](mailto:andreicbh86@gmail.com) (A. Briones-Hidrovo).

<sup>1</sup> In substitution of “renewable energy” term, following the proposal made by Harjanne and Korhonen, (2019). It excludes biomass unless otherwise specified.

<https://doi.org/10.1016/j.ecolind.2021.107748>

Received 1 October 2020; Received in revised form 19 April 2021; Accepted 21 April 2021

Available online 1 May 2021

1470-160X/© 2021 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

2018; Kabayo et al., 2019; Santoyo-Castelazo and Azapagic, 2014). In other cases, single environmental and ecological assessments, multi-criteria decision analysis (MCDA), and single indicators (CO<sub>2</sub> emissions, land use, water consumption, etc.) were applied but to a lesser extent (Bidoglio et al., 2018; Briones-Hidrovo et al., 2019; Dias Coelho et al., 2017; Evans et al., 2009; Maxim, 2014; Mortey et al., 2017).

From an environmental perspective, the conclusions found in the literature widely differ due to the size and schemes of the hydropower plant; boundaries, scale, geographic location, approach, methodology and method followed; assumptions and exclusions, etc. For instance, Kabayo et al. (2019), who applied the life cycle approach, determined that small hydro (run-of-river, average 8.6 MW) was the most environmentally sustainable in Portugal, followed by large hydro. Other life cycle approach studies reached the same overall conclusions (Atilgan and Azapagic, 2016; Gaete-Morales et al., 2018). However, Kumar and Katoch (2016) found that the environmental impact (degradation of land, impact on aquatic life, land consumption, deforestation, etc.) of small hydro (run-of-river schemes, <25 MW, India) is not small relative to that of large hydro (dam, >100 MW). There were similarly contradictory conclusions when emergy assessment was applied. For instance, Ali et al. (2020) and Chen et al. (2020) obtained an environmental sustainability index (ESI) below 1 for two large hydropower dam models located in China. Conversely, Tassinari et al. (2016) obtained an ESI range of 26 to 60 for two different large hydropower plant models (dam and run-of-river) located in Brazil.

If the ENSU is enlarged compared to any other LCCF energy system, Maxim (2014) applied MCDA. He ranked large hydropower as the most (environmentally) sustainable power technology. This ranking was in agreement with Atilgan and Azapagic (2016) and Evans et al. (2009), even though they followed different approaches. However, Varun et al. (2010) and Onat and Bayar (2010) ranked hydro energy only second and third, respectively. This background reveals the contradictory and uncertain nature of results and conclusions of the ENSU of hydropower. Additionally, it is well-known the broad impacts of (dam) hydropower on biodiversity (Wu et al., 2019). In this sense, it is shown that the development of dam-based hydropower will disproportionately impact areas of high freshwater megafauna richness (e.g., South America), which could bring potential conflicts between climate mitigation and biodiversity conservation (Zarfl et al., 2019). Current practices for biodiversity impact mitigation are not enough, and including ecosystem services in “no net loss” strategies are needed (Jones and Bull, 2020).

## 1.2. Energy, sustainability and development

No discussion about sustainability can occur without considering the current climate and ecological setting and other key concepts. *Sustainability* is defined as the goal of seeking human-ecosystem equilibrium, and it rests on three pillars: environmental, social, and economic (Jeronen, 2013; UNESCO, 2019). There is a conceptual difference between weak and strong sustainability. As represented by classical economics, weak sustainability expresses that natural capital can be substituted by produced capital. In turn, strong sustainability, framed within the field of ecological economics, argues that natural capital is non-substitutable (Neumayer, 2003; Romero and Linares, 2014).

On the other hand, *sustainable development* refers to temporal processes and pathways that lead toward sustainability (UNESCO, 2019; Shaker, 2015). Sustainable development was globally defined as that which “meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Currently, the United Nations pursues a set of 17 sustainable development goals (United Nations, 2019).

The use of the term “development” is widespread. Still, the concept remains vague and relies on beliefs and assumptions about social progress (Rist, 2007), being firmly attached to the notion of economic growth (Escobar, 2015; Rist, 2008). Rist (2007) defines development as “the general transformation and destruction of the natural environment and

of social relations to increase the production of commodities (goods and services) geared, through market exchange, to effective demand.” The level of development achieved by a given society has mainly been measured through economic growth. That is the increase in the gross domestic product of a country (Robra and Heikkurinen, 2019). Bearing these definitions in mind, the extensive associated literature exposes the following findings and conclusions:

- No country meets the basic needs of its citizens at a globally sustainable level of resources use (O’Neill et al., 2018).
- Economic growth combined with LCCF energies deployment contributes to biodiversity loss via greater resource consumption and higher emissions (Otero et al., 2020; Rehbein et al., 2020; Sonter et al., 2020).
- There is a lack of robust evidence that absolute decoupling between economic growth and resources consumption can be achieved globally (Hickel and Kallis, 2019; Vadén et al., 2020).
- Sustainable development goals are inconsistent and act as a smoke-screen for future environmental destruction (Hickel, 2019; Zeng et al., 2020).
- Green economic growth, which relies on the generalisation of LCCF energies and bioenergy, is unfeasible since it would decrease the (standard) Energy Returned on Energy Invested (EROI) below the thresholds required to sustain the current level of industrialisation (Capellán-Pérez et al., 2019).
- Renewable (energy) does not mean sustainable (Harjanne and Korhonen, 2019).
- Green growth would not keep the global temperature below 2 °C, making it incompatible with world climate policies (Nieto et al., 2020).
- It is unlikely that LCCF energies altogether with bioenergy can meet the current power demand (Moriarty and Honnery, 2016).
- Finally, the availability of crucial metallic minerals is likely to be undermined due to the global energy transition (Valero et al., 2018b, 2018a).

## 1.3. Goal of the study

Despite these efforts, the ENSU of hydropower and its different models is still unclear from a holistic<sup>2</sup> perspective. In this context, from the literature reviewed, it was inferred that studies concerning the ENSU of hydropower are still rare; existing studies follow a single approach (e.g., Atilgan and Azapagic, 2016; Nautiyal and Goel, 2020; Santoyo-Castelazo and Azapagic, 2014); single environmental indicators are commonly used (Mekonnen and Hoekstra, 2012; Varun et al., 2010); the ENSU of hydropower is often determined on the basis of comparative electricity generation system analysis (Gaete-Morales et al., 2018; Kabayo et al., 2019), hydropower schemes are not directly compared with one another from a variety of approaches within environmental perspective (e.g., Maxim, 2014; Pang et al., 2015a); conclusions are found to be often contradictory; the ENSU operates within a weak sustainability framework; and lastly, existing studies do not use more complex biophysical indicators or present a holistic assessment (Nautiyal and Goel, 2020).

Therefore, this study aims to fill these gaps by undertaking a holistic assessment of the ENSU of hydropower. Eight biophysical indicators of different approaches and levels of complexity in their calculations were selected. For that purpose, two hydropower schemes as case studies located in Ecuador were analysed. In this way, an overall analysis of the contributions and constraints of each indicator is provided. The value of said indicators for a broader and complete ENSU assessment was discussed after that. The extent to which hydropower is or is not sustainable

<sup>2</sup> From the term holism which is the tendency to look at an object as a whole; it addresses complexity and it opposes to reductionism (Verschuren, 2001).

is evaluated, with the final aim to provide some guidelines for better decision-making in hydropower policies. The structure of the paper is as follows: Section 2 provides the addressed indicators, characteristics, and main calculations. In section 3, hydropower case studies are presented. Section 4 provides the results, their discussion, and further implications of the future development of hydropower based on this ENSU. Finally, conclusions are given in Section 5.

## 2. Methodology

The holistic ENSU assessment of hydropower is based on eight biophysical indicators, which are described below. These include six widely applied indicators (carbon footprint, energy returned on energy invested, exergy replacement cost, water footprint, water-carbon nexus, and environmental sustainability index) and two additional indicators (ecosystem services efficiency and biocapacity impact) recently proposed by Briones-Hidrovo et al. (2020, 2019). By considering a holistic approach within an environmental perspective, these indicators were selected according to the type (e.g., resources, energy, emissions, sustainability), approach (e.g., donor-side, user-side, life cycle, ecological economics), time scale (e.g., life cycle), quantity and quality representation of results (e.g., exergy, the volume of water), and data availability (Table 1). Detailed information about the calculation of each indicator can be found in the Supplementary Material.

### 2.1. Carbon footprint

Carbon footprint (CF) is defined as the sum of greenhouse gases (GHG) emissions and removals in a product system, expressed as the carbon dioxide equivalent (CO<sub>2-eq</sub>) and based on a life-cycle assessment using the single impact category of climate change (International Organization for Standardization, 2018). As far as hydropower projects are concerned, there are several GHG sources, depending on the model. For instance, GHG emissions in dam hydropower plants are related to pre-impoundment, both at the reservoir and downstream (Barros et al., 2011; Jiang et al., 2018; Kemenes et al., 2016), as well as its construction. Following ISO 14067 guidelines, the carbon footprint of hydropower (CF<sub>H</sub>) was determined as follows (Briones-Hidrovo et al., 2017):

**Table 1**  
Summary of addressed indicators and their main characteristics.

Indicator	Abb	Time scale	Approach <sup>A</sup>	What it measures
Carbon Footprint	CF <sub>H</sub>	Life cycle	User-side, Life cycle	GHG emissions
Ecosystem Services Efficiency	ESE <sub>H</sub>	Yearly	Donor-side, Ecological economics	Values and benefits to people
Exergy Replacement Cost	ERC <sub>H</sub>	Thanatia <sup>B</sup>	Donor-side, Thermodynamic	Exergy cost of Minerals
Energy Return on Energy Invested	EROI <sub>H</sub>	n/a	User-side, Cost-benefit	Quantity and quality of fuels
Water Footprint	WF <sub>H</sub>	Life cycle	User-side, Life cycle	Quantity of water resource
Water-Carbon Nexus	WCN <sub>H</sub>	Life cycle	User-side, Nexus	Link between water resource and carbon emissions
Environmental Sustainability Index	ESI <sub>H</sub>	Yearly	Donor-side, Thermodynamic	Sustainability of the system
Biocapacity Impact	Bi <sub>H</sub>	Yearly	Donor-side, Thermodynamic <sup>C</sup>	Ecosystem capacity loss

<sup>A</sup> Based on Romero and Linares (2014).

<sup>B</sup> It refers to the baseline Crepuscular Earth model of the theoretical dispersed Earth proposed by Valero et al. (2011a) and Valero et al. (2011b).

<sup>C</sup> Following energy principle.

$$CF_H = C + E + R + X \tag{1}$$

C, R, and X are the GHG emissions generated by the construction, the reservoir, the turbines, spillways, and downstream, respectively; E stands for losses in the terrestrial ecosystem and, hence, the loss of carbon sequestration and storage capacity.

### 2.2. Ecosystem services efficiency

The Ecosystem Services Assessment (ESA) entails either the biophysical or the monetary valuation of the ecosystem services (ES) provided by identified ecosystems from an ecological, economic perspective. Harnessing one or several ES (e.g. water) implies the degradation or even the loss of other ES, thereby directly and indirectly undermining the benefits and welfare of human beings (Millennium Ecosystem Assessment, 2005). In this sense, the hydropower ecosystem services efficiency (ESE<sub>H</sub>, dimensionless), defined as the ratio between the total economic value of ES before and after the construction of hydropower, is regarded as the best way to assess the impact of hydro-power upon the ES framework (Briones-Hidrovo et al., 2019). Then,

$$ESE_H = \frac{ES_a}{ES_b} \tag{2}$$

where ES is the total value of all ecosystem services supplied before (b) and after (a) the construction of the hydropower project, in \$/year.

### 2.3. Exergy replacement cost

The development and implementation of LCCF energy technologies are highly dependent on both fuel and non-fuel mineral resources. These resources can be assessed from a thermodynamic perspective. The exergy of a mineral deposit is defined as the minimum energy required to restore the mineral deposit from a degraded state to natural conditions. The exergy of a mineral is based on two main components: the chemical composition and the concentration (Valero et al., 2014). In this context, the exergy replacement cost (ERC) can be used as an indicator to determine the sustainability of non-renewable resource depletion caused by the construction of a hydropower plant (Valero et al., 2013; Whiting et al., 2017):

$$ERC_H = \frac{\sum ERC_F \times m_F + \sum ERC_N \times m_N}{3.6} \tag{3}$$

ERC<sub>H</sub> is the total exergy replacement cost of hydropower in TWhex. ERC and m are the exergy replacement cost (GJ/t) and the quantity (t) of fuel F and non-fuel N minerals used throughout the life cycle.

### 2.4. Energy returned on energy invested

The energy returned on energy invested (EROI) standard dimensionless indicator can be regarded as a means of measuring the quality of various fuels. It is defined as the ratio between the energy delivered by a particular fuel and the energy invested in the capture and delivery of this energy (Hall et al., 1979, 2014):

$$EROI_H = \frac{E_D}{E_R} \tag{4}$$

where EROI<sub>H</sub> is the energy returned on energy invested of hydropower, E<sub>D</sub> is the energy delivered by the system, and E<sub>R</sub> is the energy required to deliver E<sub>D</sub>, and both are expressed in the same energy units.

### 2.5. Water footprint

The water footprint (WF) measures the appropriation of freshwater resources by humans. This appropriation is related to water volumes consumed (evaporated, incorporated into a product) or polluted

(Mekonnen and Hoekstra, 2011). Water consumption also includes the water that evaporates, is consumed either by humans or livestock, does not return to the river basin, and is diverted from surface-water sources (Bakken et al., 2017; Pfister et al., 2011). Different methods and approaches are currently used to determine the WF of a product or service (Quinteiro, 2018). Bearing in mind the complexity of hydropower generation when it comes to water resources, the water footprint of hydropower ( $WF_H$ ,  $hm^3/GWh$ ) is determined following the methodology proposed by Dias Coelho et al. (2017) in which net evaporation, water diversion, and withdrawal are closely connected:

$$WF_H = \frac{(E_0 - E_1) + W_{d,w}}{P} \quad (5)$$

where  $E_1$  is the evaporation from the reservoir ( $hm^3/year$ ),  $E_0$  is the evapotranspiration before dam construction ( $hm^3/year$ ).  $W_{d,w}$  is the water volume either diverted or withdrawn that does not return to the watershed ( $hm^3/year$ ).  $P$  is the average hydropower generation (GWh/year).

## 2.6. Water-carbon nexus

Hydropower is usually implemented to diminish GHG emissions. However, this implies the use and consumption of water resources. Hence, CF and WF complement each other. Following Zhang et al. (2018), the water-carbon nexus of hydropower ( $WCN_H$ ,  $m^3/kg CO_{2-eq}$ ) expresses the quantity of water that needs to be consumed to reduce a unit of  $CO_2$  emissions:

$$WCN_H = \frac{Wc}{(CF_1 - CF_2) \times P} \quad (6)$$

where  $Wc$  is the total annual water consumed ( $m^3/year$ ),  $CF_1$  and  $CF_2$  are the GHG emissions of the locally replaced fossil-fuel power plant and hydropower project, respectively ( $kg CO_{2-eq}/MWh$ );  $P$  is the average hydropower generation (MWh/year).

## 2.7. Emergy assessment

The term “emergy” follows Odum’s theory of energy quality. Emergy is defined as the availability of energy (exergy) of one kind (usually solar) used in transformations both directly and indirectly to provide a given flow or storage of energy or matter. The unit of emergy is the solar emergy Joules, seJ (Brown and Ulgiati, 2004a). In emergy analysis, the overall environmental load and the sustainability of a given system is determined using an eco-thermodynamic approach (Pang et al., 2015a). In this regard, the Environmental Sustainability Index of hydropower ( $ESI_H$ ), based on the Emergy Yield Ratio ( $EYR_H$ ) and the Environmental Load Ratio ( $ELR_H$ ), is calculated following Pang et al. (2015):

$$ESI_H = \frac{EYR_H}{ELR_H} = \frac{\frac{U}{F+L_{ES}}}{\frac{N+F_N+L_{N-ES}}{R+F_R}} \quad (7)$$

where  $U$  is the total emergy use,  $N$  is the free local non-renewable resources,  $R$  is the free local renewable resources,  $F$  is the total resources purchased from the economy (inputs),  $F_N$  is the non-renewable fraction of the purchased inputs,  $F_R$  is the renewable fraction of the purchased inputs, and  $L_{ES}$  is the ecosystem service losses which are regarded as non-renewable ( $L_{N-ES}$ ).

## 2.8. Biocapacity impact

Biocapacity refers to the amount of biologically productive land and water areas available. In other words, ecosystems can produce biological materials and absorb waste material generated by humans under the current management schemes and extraction technologies and within the boundaries of a given country (Lin et al., 2019). In this sense, when a

hydropower project is developed, biologically productive land and water are usually lost. Consequently, ecosystem services are also lost. The hydropower biocapacity impact ( $Bi_H$ , %) variable aims to link biocapacity and ecosystem services and, accordingly, to evaluate the impact of a hydropower project on the biocapacity of a given country. Based on the previously defined ecosystem services and emergy assessment, the  $Bi_H$  is calculated as follows:

$$Bi_H = \frac{Em_h}{Em_c} \quad (8)$$

$Em_h$  is the emergy related to ES losses and the extraction of local non-renewable resources involved in the construction of hydropower projects.  $Em_c$  is the total renewable emergy inputs in a country, including local non-renewable resource extraction such as forestry, fishery, and topsoil. These inputs are taken into consideration because they constitute the flows that contribute to the natural operation of ecosystems, allowing both the production of goods and services and the absorption of waste materials (Coscieme et al., 2014).

## 3. Case studies

### 3.1. Hydropower and the energetic matrix of Ecuador

Based on its Constitution (2008) and following the *Buen Vivir* National Plan (Senplades, 2009), Ecuador has aimed to change its energetic matrix to reach energy sovereignty and environmental sustainability, being the power generation sector the central axis. In this context, it was planned to substitute fossil fuel-based power generation for LCCF energy sources, specifically hydropower (MEER, 2012). The country has a techno-economic hydropower potential of 21.5 GW, 90% in the Amazonian Slope. Thus, most developed and projected hydropower plants are located in hilly areas (see Fig. 1). From 1990 until 2007, Ecuador had barely developed less than 10% of its hydropower potential (Castro, 2011; Meer, 2012). To date, the country has a hydropower installed capacity of 5.06 GW, generating 88% of national electricity demand<sup>3</sup> (Arconel, 2018a).

The accelerated deployment of hydropower was due to the hydropower potential and the environmental sustainability improvement of the power sector and sought socio-economic changes and development. In this sense, an entire hydropower-based power generation was aimed at introducing induction cooking, electric water heaters, electric vehicles to reach 100% electrification coverage. New electricity demand in the industrial sector (mining, cement, and steel) replacing fossil fuels and supporting new transportation systems such as tram and subway would turn the country into a net electricity exporter (MEER, 2012). This way, the country would reduce the imports of petroleum products and stop importing electricity from Colombia and Peru. Nevertheless, Carvajal et al. (2017) indicated that hydropower generation in Ecuador is highly uncertain and sensitive to climate change which could put at risk the power generation system and trigger side effects such as the run of oil-based power plants and increase national greenhouse gases emissions. Moreover, the authors highlighted that dam-based hydropower plants are less sensitive than run-of-river hydropower plants, and they presented a specific climate-risk control advantage. Therefore, the study Carvajal et al. (2017) put into question to what extent hydropower should be developed.

### 3.2. Hydropower plants

Two different hydropower plant schemes were analysed: Baba hydropower plant (BHP), with an installed capacity of 42 MW and is located on the central coast of Ecuador (Pacific slope) (Fig. 1). With a

<sup>3</sup> <https://www.regulacioneolica.gob.ec/balance-nacional/>



(e.g., ecosystem loss, reservoir, etc.), thereby distinguishing this way from common hydropower CF or life cycle studies. Another example is ERC that not only metallic minerals but also mineral fuels were included. In the emergy assessment, ecosystem services losses were considered what hence turned out in a lower ESI for BHP.

In comparison, MDHP obtained a greater ESI, far from the range. WF included evapotranspiration and its balance; that is to say, the evapotranspiration before and after reservoir construction in the case of BHP, differing likewise from common hydropower WF studies. What is more, water transfer was considered as consumption following the WF concept. This is why the WF of BHP resulted in being out of the range despite increasing the net electricity generation injected into the grid. In the case of MDHP, its WF included the decrease of water availability within the watershed. Remarkably, the WCN was adapted and based on the nexus of CF and WF, differing this way from the original proposal of Zhang et al. (2018), who instead considered the water storage capacity of the reservoir. Details of calculations can be found in [Supplementary Material](#).

Each addressed indicator aims to express certain information in a specific manner and it measures a well-defined aspect of the global sustainability landscape (Romero and Linares, 2014). However, indicators fail to yield a broader and deeper perspective due to their limitations (e.g., exergy, Maes and Van Passel (2014); CF, Laurent et al. (2012); WF, energy, Laurent and Owsianiak (2017)) that instead make indicators to complement each other. Moreover, the relevance of each indicator depends not only on the system under analysis but also on the geographic location and local ecosystems. For instance, WF could be highly important in the case of hydropower. However, this indicator is limited to indicate the quantity of water consumed; a contained and shared information, for instance, by ESE indicator. As Ecuador has plenty of water resources, the WF indicator is not quantitatively relevant enough for environmental sustainability assessment. Therefore, the quality of water, to what extent it is degraded, and the effects on ecosystems processes cannot be known.

Consequently, quality aspects of water and impacts on ecosystems are instead contained and expressed by ESE and Bi indicators. These indicators altogether with CF, WF, WCN, and ESI are framed and limited to ecosystems and renewable resources, exposing quantitative information except for ESI and Bi. By contrast, EROI and ERC are both qualitative and donor-side indicators, which are limited to energy, exergy, and non-renewable resources.

Common environmental sustainability assessments of hydropower include one or two biophysical indicators at most, being carbon emissions (kg CO<sub>2-eq</sub>/MWh) the most widely used (Nautiyal and Goel, 2020). In this sense, several studies did not conclude whether to what extent hydropower schemes should be or not developed (Atilgan and Azapagic, 2016; Kabayo et al., 2019; Varun et al., 2010). Furthermore, the actual biophysical impact was unknown. The pattern of having close results between different hydropower schemes and sizes is commonly found in the literature. In such cases, environmental data were poorly considered (Akber et al., 2017; Maxim, 2014; Santoyo-Castelazo and Azapagic, 2014).

Consequently, one could not certainly tell whether hydropower and overall LCCF energy systems are environmentally sustainable. Even when studies determined the environmental unsustainability of hydropower from one single approach (Chen et al., 2020; Pang et al., 2015a), it is worth having the whole picture of the environmental issues of the LCCF energy system under analysis to contrast with the national conditions (ecosystems, renewable and non-renewable resource, energy matrix, etc.). On the other hand, it should be noted that the type of indicator and approach considered is highly relevant and how it is calculated, and what data is included.

The literature indeed shows conclusions of various hydropower case studies that oppose and questions each other. For instance, Laborde et al. (2020) contradict Gaete-Morales et al. (2018) by pointing out that plans to exploit substantial hydropower potential in Chile directly oppose the

requirement to protect unique native freshwater fish fauna. Furthermore, Chile is a water-stressed country (Mekonnen and Hoekstra, 2016), which could be conflicting with water resources and biodiversity. Likewise, Kumar and Katoch (2016), who addressed the ENSU of run-of-river hydropower plants in India, argue that the impact of small hydropower plants is proportionally more significant than that of large hydropower plants. That goes in hand with the conclusions reached by Bidoglio et al. (2018). Conversely, Nautiyal et al. (2011) and Varun et al. (2010) put hydropower as an environmentally sustainable power generation option. In this same vein, the results of Tassinari et al. (2016) fall in contradiction with what has been stated by other authors concerning hydropower development in Brazil (Fearnside, 2014; Kahn et al., 2014). Lastly, on the emergy approach side, the results obtained by Chen et al. (2020) and Zhang et al. (2016) suggest that hydropower is environmentally unsustainable in China since the ESI is below 1. However, those results conflict with the studies and results of Zhang et al. (2014) and Cui et al. (2011), who obtained ESI above 1.

As discussed above, even though the existing methodologies and approaches for determining the environmental and ecological impacts of hydropower, it is still difficult to be assertive concerning its sustainability in environmental terms. The confusing picture arises from insufficient information, which leads to uneven and unreliable sustainability weighting processes. In this manner, the inclusion of more indicators could provide a better picture of each LCCF energy system, and hence, the ENSU of different LCCF energy systems could be determined more reliably while also considering the availability of local resources and ecological conditions. As pointed out by Nautiyal and Goel (2020), there is little merit in predicting the (environmental) sustainability of hydropower projects without considering nearly all forms of associated biophysical impact.

#### 4.1. Reframing the environmental sustainability of hydropower

In addition to the given sustainability and development background, it should also be borne in mind that the economy is an open subsystem integrated into the global system –Planet Earth–, and that the societal and economic dimensions cannot be divorced from the ecological dimension (Daly and Farley, 2004; Martinez-Alier, 2015). In this context, the analysis of the environmental sustainability of hydropower can be carried out from two perspectives: i) the reference energy system and ii) the biophysical boundaries.

##### 4.1.1. From the perspective of energy system

Suppose the reference energy system is a fossil-fuel power plant (a joint base scenario). In that case, two main justifications for hydropower deployment and development can be applied: i) the reduction in consumption of fossil fuels, and hence the reduction of GHG emissions, which is linked to energy-climate policies; and ii) the use of a renewable resource such as water, which is an endless and clean energy source. In this way, both BHP and MDHP are undoubtedly more environmentally sustainable than fossil fuels in quantitative terms (e.g., GHG emissions), as demonstrated by several studies (Gaete-Morales et al., 2018; Kabayo et al., 2019). Thus, it is the usual reasoning behind public energy policies: for instance, in Ecuador during the period 2007–2017 (MEER, 2012; SENPLADES, 2009) or in countries such as China, Turkey, or Austria, which are either highly dependent on fossil fuel to produce electricity or still need to import fossil fuels (Erdogdu, 2011; Li et al., 2018, 2015; Wagner et al., 2015).

However, suppose the reference energy system is another hydropower project (second option). In that case, BHP is much less environmentally sustainable than MDHP, as has been demonstrated in qualitative-quantitative terms. The third option is to consider other LCCF energy systems for reference, for instance, an onshore wind power plant. According to the literature, they have an average CF of 12 kg CO<sub>2-eq</sub>/MWh (Dolan and Heath, 2012), an average EROI of 18:1 (Hall et al., 2014), an average WF of 21.6 m<sup>3</sup>/GWh (Mekonnen et al., 2015) and an

ESI of 25.4 (Brown and Ulgiati, 2004b). In this case, only MDHP would still be more efficient and environmentally sustainable; it has greater EROI and ESI and a lower CF, although its WF is higher than in BP. Besides, hydropower is highly reliable and flexible and does not suffer intermittency (Evans et al., 2009). Unfortunately, the evidence is that both the second and third options are rarely adopted. It is taken for granted that LCCF energies such as hydropower plants (HP) are environmentally sustainable and helpful tools to fight against climate change. And it is assumed independently from the HP type, despite existing evidence to the contrary (Briones-Hidrovo et al., 2020; Gibson et al., 2017; Kahn et al., 2014).

#### 4.1.2. From the perspective of biophysical boundaries

A fourth option is to analyse the ENSU of hydropower from the perspective of biophysical boundaries. In this regard, the central question is how many hydropower plants can be built within the national biophysical boundaries. Since 2007, public energy policies in Ecuador have aimed to exploit hydroelectric potential as a vital component of the energy matrix shift. Following this, countless hydropower projects have been planned to meet current and future national electricity demand more sustainably (ARCONEL, 2015; MEEER, 2012).

According to Moriarty and Honnery (2016), LCCF energy and bioenergy potential should be limited if ecosystem services are to be maintained, which agrees with the conclusions reached by Briones-Hidrovo et al. (2019). Furthermore, they argue that the energy costs of maintaining ecosystem services also rise with LCCF energy and bioenergy output, particularly for bio and hydro energy. Gasparatos et al. (2017) presented solid evidence that LCCF energy and bioenergy expansion causes habitat changes and loss, leading to changes in the ecosystem and biodiversity loss. Concerning this, the deployment and acceleration of dam construction will increase even more the already large number of fragmented rivers worldwide. Currently, only 23% of rivers (of over 1000 km in length) flow into the sea uninterrupted (Grill et al., 2019; Zarfl et al., 2015).

Moreover, LCCF energies add to fossil fuel power capacity instead of replacing them (York and Bell, 2019). In this sense, and considering the background presented, it could be argued that the ultimate drivers behind the implementation of LCCF energy sources such as hydropower are economic growth and development, thereby making LCCF energies environmentally unsustainable. York and Bell (2019) have also revealed that a full energy transition will not be achieved by merely promoting LCCF energy and bioenergy according to historical energy patterns. They claimed it should not be assumed that an increase in LCCF energy production is equal to moving away from fossil fuels.

Secondly, based on the evidence, it can be argued that environmental sustainability should be a matter of limits (Fitzpatrick and Mullally, 2019; O'Neill et al., 2018) and, therefore, be regarded as the starting point of any ENSU assessment. Because of the false dichotomy between LCCF energies and fossil fuels,<sup>4</sup> the overall development of any LCCF energy project is not called into question, and biophysical boundaries are overlooked. Accordingly, not only should the most environmentally sustainable models be promoted (for instance, MDHP), but the maximum amount of LCCF energy resource to be exploited without crossing local biophysical boundaries should be clearly defined.

<sup>4</sup> Energy and climate public policies focus on promoting renewable energies and decarbonising the economy in order to mitigate climate change, under the green growth paradigm. This is a central target for the current sustainable development goals (United Nations, 2019). In this context, climate change is perceived solely in terms of emissions and the source of energy (fossil fuels). The confrontation between fossil fuels and renewable energies precludes recognising the existence of biophysical boundaries and the need for a post-growth approach in order to limit global warming to 1.5°C and prevent the loss of ecosystems and biodiversity (Gielen et al., 2019; IPBES, 2019; Nieto et al., 2020).

Both hydropower case studies are a good illustration of the given arguments. The more MDHP-type facilities built, the more significant the impact on resources, ecosystems, and biodiversity. For instance, one MDHP has a Bi equal to 0.003% of the actual national biocapacity, but 100 MDHP would lead to a biocapacity impact of 0.3%. Likewise, ten BHP-type facilities would lead to a biocapacity impact of 1.8%. Therefore, limits should be considered if resources, ecosystems, and biodiversity are to be preserved, especially in Ecuador, which is characterized by its great biological diversity. It should be noted that hydropower potential, as in the case of MDHP, is limited by geographic and hydrological conditions. Finally, it is worth noting that a weighting process is not introduced since this would unduly simplify and limit the information conveyed by each indicator.

#### 4.2. Implications for future hydropower development

Since the world is facing a climate-ecological crisis, the deployment and development of hydropower should be taken with more caution due to the environmental impacts and sustainability at the national level. In this sense, addressing such indicators presented in this study will allow decision-makers to be well informed of the environmental performance of each hydropower project in a broader sense. That would change how this LCCF energy source is conceived and the environmental implications of becoming the country as a net energy exporter. Application of the whole set of indicators is highly encouraged in the new HP projects in Ecuador, taking into account its energy planning based on several HP projects and specific locations similar to the two case studies here presented.

By establishing such a set of biophysical indicators as part of the environmental assessment and taking the biophysical boundaries as the base point, the national hydropower potential will be affected, reducing it to set environmental sustainability parameters. This way, the ecological flow, the schemes of hydropower plants, and power generation planning would be reframed altogether with power demand. Moreover, it would allow in-depth analysis and better comparison among LCCF energy system options. It means that alternatively, other sources of LCCF energy sources should be considered (Moya et al., 2018) and compared with hydro energy to be assertive with the best environmentally option to be developed.

The holistic environmental approach adopted in this study should be later included in a global sustainability assessment where the need for new LCCF energy systems for power generation is questioned and discussed. Furthermore, hydro energy policies should be reframed to protect and restore ecosystems and biodiversity while achieving environmental sustainability.

## 5. Conclusions

The current study addresses the environmental sustainability of hydropower using eight biophysical indicators. For such purpose, two different hydropower plants schemes are taken as study cases. From the results, several conclusions are drawn. Firstly, it is demonstrated that MDHP (run-of-river scheme) is by far more environmentally sustainable than its counterpart, BHP (dam scheme). This then suggests that all hydropower plants are not environmentally sustainable in an equal manner, and therefore, the implementation of dam-based hydropower plants should be taken with caution. This suggestion agrees with the conclusions reached by previous studies that highlight the high impact of dam-based hydropower plants on biodiversity, especially in tropical areas. Secondly, it is found that using fewer indicators leads to uneven and unreliable environmental sustainability weighting processes. Hence, the more indicators are taken into account, the better the understanding of the environmental performance of hydropower will be. Thirdly, the proposed assessment in this work allows having more robust criteria for decision-making processes and energy policies at the national level. Fourthly, depending on the energy system of reference, the

environmental sustainability of hydropower could be taken either as positive or negative. Accordingly, both different hydropower sizes and schemes as other LCCF energy systems should be considered for comparison purposes. Finally, the proposed assessment is not restricted to the indicators here addressed, and hence, other indicators should be included when possible. Likewise, extending and applying the proposed assessment to other LCCF energy systems is suggested, contributing this way with a fair and equitable comparison. Lastly, biophysical boundaries should be included in future environmental sustainability assessments if ecosystems and biodiversity are to be preserved. This should be extended to all LCCF energy systems.

### CRedit authorship contribution statement

**Andrei Briones-Hidrovo:** Writing - original draft, Resources, Formal analysis, Conceptualization, Investigation, Writing - review & editing. **Javier Uche:** Writing - original draft, Validation, Formal analysis, Conceptualization, Visualization, Supervision, Writing - review & editing. **Amaya Martínez-Gracia:** Writing - original draft, Validation, Formal analysis, Conceptualization, Visualization, Supervision, Writing - review & editing.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2021.107748>.

### References

- Akber, M.Z., Thaheem, M.J., Arshad, H., 2017. Life cycle sustainability assessment of electricity generation in Pakistan: Policy regime for a sustainable energy mix. *Energy Policy* 111, 111–126. <https://doi.org/10.1016/j.enpol.2017.09.022>.
- Ali, M., Liu, L., Geng, Y., Khokhar, S., 2020. Emery based sustainability evaluation of a hydroelectric dam proposal in South Asia. *J. Clean. Prod.* 264, 121496. <https://doi.org/10.1016/j.jclepro.2020.121496>.
- ARCONEL, 2018a. Atlas del Sector Eléctrico Ecuatoriano. Quito.
- ARCONEL, 2018b. Mapa No3: Centrales de generación hidráulica. Quito.
- ARCONEL, 2015. Proyectos Hidroeléctricos en estudio a lo largo de las vertientes Río Amazonas y Pacífico. Quito.
- Atilgan, B., Azapagic, A., 2016. An integrated life cycle sustainability assessment of electricity generation in Turkey. *Energy Policy* 93, 168–186. <https://doi.org/10.1016/j.enpol.2016.02.055>.
- Bakker, T.H., Killington, Å., Alfreðsen, K., 2017. The water footprint of hydropower production-state of the art and methodological challenges. *Glob. Challenges* 1 (5), 1600018. <https://doi.org/10.1002/gch2.201600018>.
- Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., del Giorgio, P., Roland, F., 2011. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nat. Geosci.* 4 (9), 593–596. <https://doi.org/10.1038/ngeo1211>.
- Bidoglio, G., Berger, M., Finkbeiner, M., 2018. An environmental assessment of small hydropower in India: the real costs of dams' construction under a life cycle perspective. *Int. J. Life Cycle Assess.* 24 (3), 419–440. <https://doi.org/10.1007/s11367-018-1458-4>.
- Briones-Hidrovo, A., Uche, J., Martínez-Gracia, A., 2020. Determining the net environmental performance of hydropower: a new methodological approach by combining life cycle and ecosystem services assessment. *Sci. Total Environ.* 712, 136369. <https://doi.org/10.1016/j.scitotenv.2019.136369>.
- Briones-Hidrovo, A., Uche, J., Martínez-Gracia, A., 2019. Estimating the hidden ecological costs of hydropower through an ecosystem services balance: a case study from Ecuador. *J. Clean. Prod.* 233, 33–42. <https://doi.org/10.1016/j.jclepro.2019.06.068>.
- Briones-Hidrovo, A., Uche, J., Martínez-Gracia, A., 2017. Accounting for GHG net reservoir emissions of hydropower in Ecuador. *Renew. Energy* 112, 209–221. <https://doi.org/10.1016/j.renene.2017.05.047>.
- Brown, M.T., Ulgiati, S., 2004a. Energy quality, emery, and transformity: H.T. Odum's contributions to quantifying and understanding systems. *Ecol. Modell.* 178 (1–2), 201–213. <https://doi.org/10.1016/j.ecolmodel.2004.03.002>.
- Brown, M.T., Ulgiati, S., 2004b. Emery analysis and environmental accounting. *Encycl. Energy* 2, 329–354. <https://doi.org/10.1016/b0-12-176480-x/00242-4>.
- Capellán-Pérez, I., Castro, C.D., Javier, L., González, M., 2019. Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies Energy Return On energy Invested Energy Stored On energy Invested. *Energy Strateg. Rev.* 26, 100399. <https://doi.org/10.1016/j.esr.2019.100399>.
- Carvajal, P.E., Anandarajah, G., Mulugetta, Y., Dessens, O., 2017. Assessing uncertainty of climate change impacts on long-term hydropower generation using the CMIP5 ensemble—the case of Ecuador. *Clim. Change* 144 (4), 611–624. <https://doi.org/10.1007/s10584-017-2055-4>.
- Castro, M., 2011. Hacia una nueva matriz energética diversificada en Ecuador. CEDA, Quito.
- Chen, J., Mei, Y., Ben, Y., Hu, T., 2020. Emery-based sustainability evaluation of two hydropower projects on the Tibetan Plateau. *Ecol. Eng.* 150, 105838. <https://doi.org/10.1016/j.ecoleng.2020.105838>.
- Coscieme, L., Pulselli, F.M., Marchettini, N., Sutton, P.C., Anderson, S., Sweeney, S., 2014. Emery and ecosystem services: a national biogeographical assessment. *Ecosyst. Serv.* 7, 152–1159. <https://doi.org/10.1016/j.ecoser.2013.11.003>.
- Cui, B., Hu, B.o., Zhai, H., 2011. Employing three ratio indices for ecological effect assessment of Manwan Dam construction in the Lancang River. *China. River Res. Appl.* 27 (8), 1000–1022. <https://doi.org/10.1002/rra.1412>.
- Daly, H.E., Farley, J., 2004. *Ecological Economics: Principles and Applications*. Ecological Economics. Island Press, Washington.
- de Faria, F.A.M., Jaramillo, P., Sawakuchi, H.O., Richey, J.E., Barros, N., 2015. Estimating greenhouse gas emissions from future Amazonian hydroelectric reservoirs. *Environ. Res. Lett.* 10 (12), 124019. <https://doi.org/10.1088/1748-9326/10/12/124019>.
- Dias Coelho, C., David da Silva, D., Chohaku Sedyama, G., Castro Moreira, M., Bueno Pereira, S., Quintao Lana, A.M., 2017. Comparison of the water footprint of two hydropower plants in the Tocantins River Basin of Brazil. *J. Clean. Prod.* 153, 164–175. <https://doi.org/10.1016/j.jclepro.2017.03.088>.
- Dolan, S.L., Heath, G.A., 2012. Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power: Systematic Review and Harmonization. *J. Ind. Ecol.* 16. <https://doi.org/10.1111/j.1530-9290.2012.00464.x>.
- dos Santos, M.A., Rosa, L.P., Sikar, B., Sikar, E., dos Santos, E.O., 2006. Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants. *Energy Policy* 34 (4), 481–488. <https://doi.org/10.1016/j.enpol.2004.06.015>.
- Erdogdu, E., 2011. An analysis of Turkish hydropower policy. *Renew. Sustain. Energy Rev.* 15 (1), 689–696. <https://doi.org/10.1016/j.rser.2010.09.019>.
- Escobar, A., 2015. *Development, Critiques of*. In: Dalisa, G., Demaria, F., Kallis, G. (Eds.), *Degrowth. A Vocabulary of a New Era*. Routledge, New York, pp. 56–59.
- Evans, A., Strezov, V., Evans, T.J., 2009. Assessment of sustainability indicators for renewable energy technologies 13, 1082–1088. <https://doi.org/10.1016/j.rser.2008.03.008>.
- Fearnside, P.M., 2014. Impacts of Brazil's Madeira River Dams: unlearned lessons for hydroelectric development in Amazonia. *Environ. Sci. Policy* 38, 164–172. <https://doi.org/10.1016/j.envsci.2013.11.004>.
- Fitzpatrick, J.J., Mullally, B., 2019. Assessing environmental sustainability using ecological limits expressed as mass flowrates with the inclusion of a sustainable time perspective. *ChemEngineering* 3, 78. <https://doi.org/10.3390/chemengineering3040078>.
- Gaete-Morales, C., Gallego-Schmid, A., Stamford, L., Azapagic, A., 2018. Assessing the environmental sustainability of electricity generation in Chile. *Sci. Total Environ.* 636, 1155–1170. <https://doi.org/10.1016/j.scitotenv.2018.04.346>.
- Gasparatos, A., Doll, C.N.H., Esteban, M., Ahmed, A., Olang, T.A., 2017. Renewable energy and biodiversity: Implications for transitioning to a Green Economy. *Renew. Sustain. Energy Rev.* 70, 161–184. <https://doi.org/10.1016/j.rser.2016.08.030>.
- Gibson, L., Wilman, E.N., Laurance, W.F., 2017. How Green is 'Green' Energy? *Trends Ecol. Evol.* 32 (12), 922–935. <https://doi.org/10.1016/j.tree.2017.09.007>.
- Gielen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorini, R., 2019. The role of renewable energy in the global energy transformation. *Energy Strateg. Rev.* 24, 38–50. <https://doi.org/10.1016/j.esr.2019.01.006>.
- Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M.E., Meng, J., Mulligan, M., Nilsson, C., Olden, J.D., Opperman, J.J., Petry, P., Reidy Liermann, C., Sáenz, L., Salinas-Rodríguez, S., Schelle, P., Schmitt, R.J.P., Snider, J., Tan, F., Tockner, K., Valdujo, P. H., van Soesbergen, A., Zarfl, C., 2019. Mapping the world's free-flowing rivers. *Nature* 569 (7755), 215–221. <https://doi.org/10.1038/s41586-019-1111-9>.
- Hall, C., Lavine, M., Sloane, J., 1979. Efficiency of energy delivery systems: I. An economic and energy analysis. *Environ. Manage.* 3 (6), 493–504. <https://doi.org/10.1007/BF01866318>.
- Hall, C.A.S., Lambert, J.G., Balogh, S.B., 2014. EROI of different fuels and the implications for society. *Energy Policy* 64, 141–152. <https://doi.org/10.1016/j.enpol.2013.05.049>.
- Harjanne, A., Korhonen, J.M., 2019. Abandoning the concept of renewable energy. *Energy Policy* 127, 330–340. <https://doi.org/10.1016/j.enpol.2018.12.029>.
- Hickel, J., 2019. The contradiction of the sustainable development goals: growth versus ecology on a finite planet. *Sustain. Dev.* 27 (5), 873–884. <https://doi.org/10.1002/sd.v27.510.1002/sd.1947>.
- Hickel, J., Kallis, G., 2019. Is green growth possible? *New Polit. Econ.* 25 (4), 469–486. <https://doi.org/10.1080/13563467.2019.1598964>.
- International Organization for Standardization, 2018. ISO 14067. Greenhouse gases—Carbon footprint of products—Requirements and guidelines for quantification and communication.

- IPBES, 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services. IPBES secretariat, Bonn. <https://doi.org/https://doi.org/10.5281/zenodo.3553579>.
- IPCC, 2018. Summary for Policymakers., in: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.L., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change., World Meteorological Organization, Geneva, p. 32.
- Jeronen, E., 2013. Sustainable Development, in: Idowu, S.O., Capaldi, N., Zu, L., Gupta, A.D. (Eds.), Encyclopedia of Corporate Social Responsibility. Springer, Berlin. <https://doi.org/https://doi.org/10.1007/978-3-642-28036-8>.
- Jiang, T., Shen, Z., Liu, Y., Hou, Y., 2018. Carbon footprint assessment of four normal size hydropower stations in China. *Sustain.* 10, 1–14. <https://doi.org/10.3390/su10062018>.
- Jones, I.L., Bull, J.W., 2019. Major dams and the challenge of achieving “No Net Loss” of biodiversity in the tropics. *Sustain.* Dev. 28 (2), 435–443. <https://doi.org/10.1002/sd.v28.210.1002/sd.1997>.
- Kabayo, J., Marques, P., Garcia, R., Freire, F., 2019. Life-cycle sustainability assessment of key electricity generation systems in Portugal. *Energy* 176, 131–142. <https://doi.org/10.1016/j.energy.2019.03.166>.
- Kahn, J.R., Freitas, C.E., Petrere, M., 2014. False shades of green: the case of Brazilian Amazonian hydropower. *Energy* 7, 6063–6082. <https://doi.org/10.3390/en7096063>.
- Kemenes, A., Forsberg, B.R., Melack, J.M., 2016. Downstream emissions of CH4 and CO2 from hydroelectric reservoirs (Tucuruí, Samuel, and Curua-Una) in the Amazon basin. *Int. Waters* 6, 295–302. <https://doi.org/10.5268/IW-6.3.980>.
- Kumar, D., Katoch, S.S., 2016. Environmental sustainability of run of the river hydropower projects: A study from western Himalayan region of India. *Renew. Energy* 93, 599–607. <https://doi.org/10.1016/j.renene.2016.03.032>.
- Laborde, A., Habit, E., Link, O., Kemp, P., 2020. Strategic methodology to set priorities for sustainable hydropower development in a biodiversity hotspot. *Sci. Total Environ.* 714, 136735. <https://doi.org/10.1016/j.scitotenv.2020.136735>.
- Laurent, A., Olsen, S.I., Hauschild, M.Z., 2012. Limitations of carbon footprint as indicator of environmental sustainability. *Environ. Sci. Technol.* 46 (7), 4100–4108. <https://doi.org/10.1021/es204163f>.
- Laurent, A., Owsianiak, M., 2017. Potentials and limitations of footprints for gauging environmental sustainability. *Curr. Opin. Environ. Sustain.* 25, 20–27. <https://doi.org/10.1016/j.cosust.2017.04.003>.
- Li, X.-Z., Chen, Z.-J., Fan, X.-C., Cheng, Z.-J., 2018. Hydropower development situation and prospects in China. *Renew. Sustain. Energy Rev.* 82, 232–239. <https://doi.org/10.1016/j.rser.2017.08.090>.
- Li, Y., Li, Y., Ji, P., Yang, J., 2015. The status quo analysis and policy suggestions on promoting China's hydropower development. *Renew. Sustain. Energy Rev.* 51, 1071–1079. <https://doi.org/10.1016/j.rser.2015.07.044>.
- Lin, D., Hanscom, L., Martindill, J., Borucke, M., Cohen, L., Galli, A., Lazarus, E., Zokai, G., Ilha, K., Eaton, D., Wackernagel, M., 2019. Working Guidebook to the National Footprint and Biocapacity Accounts. Oakland.
- Maes, D., Van Passel, S., 2014. Advantages and limitations of exergy indicators to assess sustainability of bioenergy and biobased materials. *Environ. Impact Assess. Rev.* 45, 19–29. <https://doi.org/10.1016/j.eiar.2013.11.002>.
- Martinez-Alier, J., 2015. Ecological Economics, Second Edi. ed, International Encyclopedia of the Social & Behavioral Sciences. Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-08-097086-8.910008-0>.
- Maxim, A., 2014. Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis. *Energy Policy* 65, 284–297. <https://doi.org/10.1016/j.enpol.2013.09.059>.
- MEER, 2012. Plan Maestro de Electrificación 2012-2021. Quito.
- Mekonnen, M.M., Gerbens-Leenes, P.W., Hoekstra, A.Y., 2015. The consumptive water footprint of electricity and heat: a global assessment. *Environ. Sci. Water Res. Technol.* 1 (3), 285–297. <https://doi.org/10.1039/C5EW00026B>.
- Mekonnen, M.M., Hoekstra, A., 2011. National Water Footprint Accounts: The green, blue and grey water footprint of production and consumption. Value of Water Research Report Series No. 50. Delft, The Netherlands.
- Mekonnen, M.M., Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity. *Sci. Adv.* 2 (2), e1500323. <https://doi.org/10.1126/sciadv.1500323>.
- Mekonnen, M.M., Hoekstra, A.Y., 2012. The blue water footprint of electricity from hydropower. *Hydrol. Earth Syst. Sci.* 16 (1), 179–187. <https://doi.org/10.5194/hess-16-179-2012-supplement>.
- Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being. Synthesis. Washington, DC. <https://doi.org/10.1021/jo100004c>.
- Moriarty, P., Honnery, D., 2016. Can renewable energy power the future? *Energy Policy* 93, 3–7. <https://doi.org/10.1016/j.enpol.2016.02.051>.
- Mortey, E., Ofosu, E., Kolodko, D., Kabobah, A., 2017. Sustainability assessment of the bui hydropower system. *Environments* 4, 25. <https://doi.org/10.3390/environments4020025>.
- Moya, Diego, Paredes, Juan, Kaparaju, Prasad, et al., 2018. Technical, financial, economic and environmental pre-feasibility study of geothermal power plants by RETScreen – Ecuador's case study. *Renewable and Sustainable Energy Reviews* 92, 628–637. <https://doi.org/10.1016/j.rser.2018.04.027>. In this issue.
- Nautiyal, H., Goel, V., 2020. Sustainability assessment of hydropower projects. *J. Clean. Prod.* 265, 121661. <https://doi.org/10.1016/j.jclepro.2020.121661>.
- Nautiyal, H., Singal, S.K., Varun, S., 2011. Small hydropower for sustainable energy development in India. *Renew. Sustain. Energy Rev.* 15, 2021–2027. <https://doi.org/10.1016/j.rser.2011.01.006>.
- O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. *Nat. Sustain.* 1 (2), 88–95. <https://doi.org/10.1038/s41893-018-0021-4>.
- Neumayer, E., 2003. *Weak versus Strong Sustainability. Exploring the Limits of Two Opposing Paradigms*, fourth. ed. Edward Elgar Publishing, Cheltenham.
- Nieto, J., Carpintero, Ó., Miguel, L.J., de Blas, I., 2020. Macroeconomic modelling under energy constraints: Global low carbon transition scenarios. *Energy Policy* 137, 111090. <https://doi.org/10.1016/j.enpol.2019.111090>.
- Onat, N., Bayar, H., 2010. The sustainability indicators of power production systems. *Renew. Sustain. Energy Rev.* 14 (9), 3108–3115. <https://doi.org/10.1016/j.rser.2010.07.022>.
- Otero, I., Farrell, K.N., Pueyo, S., Kallis, G., Kehoe, L., Haberl, H., Plutzer, C., Hobson, P., García-Márquez, J., Rodríguez-Labajos, B., Martin, J., Erb, K., Schindler, S., Nielsen, J., Skarin, T., Settele, J., Essl, F., Gómez-Baggethun, E., Brotons, L., Rabitsch, W., Schneider, F., Pe'er, G., 2020. Biodiversity policy beyond economic growth. *Conserv. Lett.* In press 13 (4). <https://doi.org/10.1111/conl.v13.410.1111/conl.12713>.
- Pang, M., Zhang, L., Ulgiati, S., Wang, C., 2015a. Ecological impacts of small hydropower in China: Insights from an emergy analysis of a case plant. *Energy Policy* 76, 112–122. <https://doi.org/10.1016/j.enpol.2014.10.009>.
- Pang, M., Zhang, L., Wang, C., Liu, G., 2015b. Environmental life cycle assessment of a small hydropower plant in China. *Int. J. Life Cycle Assess.* 20 (6), 796–806. <https://doi.org/10.1007/s11367-015-0878-7>.
- Pfister, S., Saner, D., Koehler, A., 2011. The environmental relevance of freshwater consumption in global power production. *Int. J. Life Cycle Assess.* 16 (6), 580–591. <https://doi.org/10.1007/s11367-011-0284-8>.
- Quinteiro, P., 2018. Identification of methodological challenges remaining in the assessment of a water scarcity footprint : a review 164–180. <https://doi.org/10.1007/s11367-017-1304-0>.
- Rehbein, J.A., Watson, J.E.M., Lane, J.L., Sonter, L.J., Venter, O., Atkinson, S.C., Allan, J. R., 2020. Renewable energy development threatens many globally important biodiversity areas. *Glob. Chang. Biol.* 26, 3040–3051. <https://doi.org/10.1111/gcb.15067>.
- REN21, 2020. Renewables 2020 Global Status Report, REN21 Secretariat.
- Rist, G., 2008. *The History of Development: From Western Origins to Global Faith*, Third. ed. Zed Books, London.
- Rist, G., 2007. Development as a buzzword. *Dev. Pract.* 17 (4-5), 485–491. <https://doi.org/10.1080/09614520701469328>.
- Ritchie, H., 2017. Renewable Energy [WWW Document]. Our World Data. URL <https://ourworldindata.org/renewable-energy> (accessed 7.15.20).
- Robra, B., Heikkurinen, P., 2019. Degrowth and the Sustainable Development Goals 1–10. [https://doi.org/10.1007/978-3-319-71058-7\\_37-1](https://doi.org/10.1007/978-3-319-71058-7_37-1).
- Romero, J.C., Linares, P., 2014. Exergy as a global energy sustainability indicator. A review of the state of the art. *Renew. Sustain. Energy Rev.* 33, 427–442. <https://doi.org/10.1016/j.rser.2014.02.012>.
- Santoyo-Castelazo, E., Azapagic, A., 2014. Sustainability assessment of energy systems: Integrating environmental, economic and social aspects. *J. Clean. Prod.* 80, 119–138. <https://doi.org/10.1016/j.jclepro.2014.05.061>.
- SENPLADES, 2009. Plan Nacional para el Buen Vivir 2009-2013. Quito.
- Shaker, R.R., 2015. The spatial distribution of development in Europe and its underlying sustainability correlations. *Appl. Geogr.* 63, 304–314. <https://doi.org/10.1016/j.apgeog.2015.07.009>.
- Sonter, L.J., Dade, M.C., Watson, J.E.M., Valenta, R.K., 2020. Renewable energy production will exacerbate mining threats to biodiversity. *Nat. Commun.* 11, 6–11. <https://doi.org/10.1038/s41467-020-17928-5>.
- Tassinari, C.A., Bonilla, S.H., Agostinho, F., Almeida, C.M.V.B., Giannetti, B.G., 2016. Evaluation of two hydropower plants in Brazil: using energy for exploring regional possibilities. *J. Clean. Prod.* 122, 78–86. <https://doi.org/10.1016/j.jclepro.2016.01.077>.
- UNESCO, 2019. Sustainable Development [WWW Document]. URL <https://en.unesco.org/themes/education-sustainable-development/what-is-esd/sd#:~:text=Sustainability%20is%20often%20thought%20of%20research%20and%20technology%20transfer%2Ceducation> (accessed 6.8.20).
- United Nations, 2019. *The Sustainable Development Goals Report*. New York.
- Vadén, T., Lähde, V., Majava, A., Järvensivu, P., Toivanen, T., Hakala, E., Eronen, J.T., 2020. Decoupling for ecological sustainability: a categorisation and review of research literature. *Environ. Sci. Policy* 112, 236–244. <https://doi.org/10.1016/j.envsci.2020.06.016>.
- Valero, Alicia, Valero, Antonio, 2013. Exergy Replacement Cost of Mineral Resources Exergy Replacement Cost of Mineral Resources. <https://doi.org/10.5890/JEAM.2013.05.004>.
- Valero, A., Valero, A., Calvo, G., Ortego, A., 2018a. Material bottlenecks in the future development of green technologies. *Renew. Sustain. Energy Rev.* 93, 178–200. <https://doi.org/10.1016/j.rser.2018.05.041>.
- Valero, A., Valero, A., Calvo, G., Ortego, A., Ascaso, S., Palacios, J.L., 2018b. Global material requirements for the energy transition. An exergy flow analysis of decarbonisation pathways. *Energy* 159, 1175–1184. <https://doi.org/10.1016/j.energy.2018.06.149>.
- Valero, A., Valero, A., Gómez, J.B., 2011a. The crepuscular planet. A model for the exhausted continental crust. *Energy* 36 (1), 694–707. <https://doi.org/10.1016/j.energy.2010.09.034>.

- Valero, A., Agudelo, A., Valero, A., 2011b. The crepuscular planet. A model for the exhausted atmosphere and hydrosphere. *Energy* 36 (6), 3745–3753. <https://doi.org/10.1016/j.energy.2010.07.017>.
- Valero, A., Carpintero, Ó., Valero, A., Calvo, G., 2014. How to account for mineral depletion. The exergy and economic mineral balance of Spain as a case study. *Ecol. Indic.* 46, 548–559. <https://doi.org/10.1016/j.ecolind.2014.07.021>.
- Varun, Prakash, R., Bhat, I.K., 2010. A figure of merit for evaluating sustainability of renewable energy systems. *Renew. Sustain. Energy Rev.* 14 (6), 1640–1643. <https://doi.org/10.1016/j.rser.2010.02.003>.
- Verschuren, J.M.P., 2001. Holism versus reductionism in modern social science research. *Qual. Quant.* 35, 389–405. <https://doi.org/10.1023/A:1012242620544>.
- Wagner, B., Hauer, C., Schoder, A., Habersack, H., 2015. A review of hydropower in Austria : past, present and future development. *Renew. Sustain. Energy Rev.* 50, 304–314. <https://doi.org/10.1016/j.rser.2015.04.169>.
- WCED, 1987. *Our Common Future*. United Nations Commission, United Nations, Oslo.
- Whiting, K., Carmona, L.G., Carrasco, A., Sousa, T., 2017. Exergy replacement cost of fossil fuels: closing the carbon cycle. *Energies* 10, 1–21. <https://doi.org/10.3390/en10070979>.
- Wu, H., Chen, J., Xu, J., Zeng, G., Sang, L., Liu, Q., Yin, Z., Dai, J., Yin, D., Liang, J., Ye, S., 2019. Effects of dam construction on biodiversity: a review. *J. Clean. Prod.* 221, 480–489. <https://doi.org/10.1016/j.jclepro.2019.03.001>.
- York, R., Bell, S.E., 2019. Energy transitions or additions?: why a transition from fossil fuels requires more than the growth of renewable energy. *Energy Res. Soc. Sci.* 51, 40–43. <https://doi.org/10.1016/j.erss.2019.01.008>.
- Zarfl, C., Berlekamp, J., He, F., Jähnig, S.C., Darwall, W., Tockner, K., 2019. Future large hydropower dams impact global freshwater megafauna. *Sci. Rep.* 9, 1–10. <https://doi.org/10.1038/s41598-019-54980-8>.
- Zarfl, C., Lumsdon, A.E., Tockner, K., 2015. A global boom in hydropower dam construction 161–170. <https://doi.org/10.1007/s00027-014-0377-0>.
- Zeng, Y., Maxwell, S., Runting, R.K., Venter, O., Watson, J.E.M., Carrasco, L.R., 2020. Environmental destruction not avoided with the Sustainable Development Goals. *Nat. Sustain.* <https://doi.org/10.1038/s41893-020-0555-0>.
- Zhang, J., Xu, L., Cai, Y., 2018. Water-carbon nexus of hydropower: the case of a large hydropower plant in Tibet. *China. Ecol. Indic.* 92, 107–112. <https://doi.org/10.1016/j.ecolind.2017.06.019>.
- Zhang, L., Pang, M., Wang, C., Ulgiati, S., 2016. Environmental sustainability of small hydropower schemes in Tibet: an emergy-based comparative analysis. *J. Clean. Prod.* 135, 97–104. <https://doi.org/10.1016/j.jclepro.2016.06.093>.
- Zhang, L.X., Pang, M.Y., Wang, C.B., 2014. Emergy analysis of a small hydropower plant in southwestern China. *Ecol. Indic.* 38, 81–88. <https://doi.org/10.1016/j.ecolind.2013.09.037>.