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HYDROPOWER DEVELOPMENT PERSPECTIVES IN THE CONTEXT OF CLIMATE CHANGE AND ENVIRONMENTAL PROTECTION

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Abstract

Climate change, the effects of which are already visible, could cause profound damage to the environment in the coming decades. In order to limit global warming to below 2°C above pre-industrial levels, human society must drastically reduce greenhouse gas emissions and make energy consumption more efficient. Although the share of renewable energy sources has increased in recent years, fossil fuels are still widely used. Given the very possible increase in energy demand, the transition to green energy will be a major challenge. Currently, among renewable energy sources, hydropower has the largest contribution to electricity production. Although it is a renewable source, hydropower is not entirely environmentally friendly. Because of this and not only, in the future a massive increase of the other renewable sources (solar, wind, etc.) is foreseen and desired. Based on specific analytical research, this study examines the current state of hydropower and development prospects in the context of climate change and risks to the environment and human health. The future development of hydropower will depend quite a lot on a number of economic, social or environmental factors. Thus, the contribution of hydropower to achieving the objectives of the Paris Agreement is uncertain. Due to its flexibility, hydropower is necessary for the global energy system and must be developed with a minimization of the impact on the environment.
Keywords: climate change, renewable energy, hydropower, dams, environmental protection

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1. Introduction

It is clear that the Earth is facing many environmental changes, the most worrying of which are climate change. The effects of climate change can be serious for people, settlements and human activities. Also, some components of the natural environment, such as biodiversity or soils, can suffer greatly. Another widely accepted fact is that current climate change is due to rising concentrations of greenhouse gases in the atmosphere, especially carbon dioxide. With the Industrial Revolution, the concentration of CO_2 in the atmosphere increased significantly, from about 280 parts per million (ppm) at the end of the 18th century to 416 ppm in January 2022 (NOAA-ESRL, 2022). The use of fossil fuels, especially coal, to obtain electricity is one of the main causes of the increase in the concentration of carbon dioxide in the atmosphere.

According to the 2015 Paris Agreement, in order to avoid the serious effects of climate change on the environment, global warming should be limited to well below 2°C, preferably 1.5°C, compared to the pre-industrial period. To achieve this long-term goal, the states of the world must reach the global peak of greenhouse gas emissions as soon as possible to create a climate-neutral world by the middle of the century (UN, 2022). Thus, renewable energy sources must replace fossil fuels, which continue to dominate world electricity production with a share of over 60%, as soon as possible. This conversion will be a major challenge as electricity consumption is expected to double by 2050 from 2019 (IAEA, 2020).

Although renewable energy sources have grown steadily in recent decades, their share of global electricity production is about 25%, ranking second to coal (IEA, 2020b). Among renewable energy sources, hydropower has the largest contribution to electricity production. Compared to fossil fuel power plants, hydropower plants are a source of energy with low greenhouse gas emissions. If hydropower were to be replaced by burning coal to generate electricity, between 3-4 billion tonnes of additional greenhouse gases would be emitted each year, and global fossil fuel and industrial emissions would be around 9% - 10% higher (Berga, 2016; IHA, 2020). In addition, the use of hydropower instead of coal avoids the production of approximately 150 million tonnes of air-polluting particles, 60 million tonnes of sulfur dioxide and 8 million tonnes of nitrogen oxides (IHA, 2020).

Based on the large volumes of water in the storage lakes, hydropower plants are a flexible source of electricity, and can operate without interruption for long periods of time. Thus, hydropower plants can be an essential support for other renewable energy sources (wind, solar), which operate intermittently, and can play a key role in the transition to clean energy. Despite the high construction costs, hydropower plants are a financially competitive source of electricity, being able to produce electricity for up to about 100 years. Hydropower projects can also provide water for agriculture, population and industry and can help mitigate the impact of extreme weather events, such as floods. They can also provide transportation, aquaculture and leisure opportunities.

2. Materials și methods

The statistical data used were taken from the databases of the International Energy Agency, the International Renewable Energy Agency, the International Hydropower Association, the International Commission on Large Dams or Our World in Data, which regularly collect and publish energy data. Some data were represented graphically in order to track the time dynamics of the installed hydropower capacity in relation to the total renewable energy capacity and the hydropower production in relation to the total renewable energy production. Scenarios for the future development of hydropower have been based on data published in 2020 and 2021 by the International Renewable Energy Agency and the International Energy Agency. The role of hydropower in the global effort to combat climate change and its negative effects on the environment have been based on a number of scientific articles published in various journals and other sources. In general, the examination of the current state of hydropower and the development prospects in the context of climate change and the risks to the environment and human health were based on specific analytical research.

3. Results

Hydropower, one of the oldest sources of energy, uses the power of moving water to generate electricity. The first hydroelectric installations appeared in Great Britain and the United States in the second half of the 19th century (Kumar et al. 2011). Since then, this source of energy has grown continuously. Currently, there are several types of hydropower plants, the most common being those with reservoirs, including pumped storage hydropower plants. The variety is much higher if we refer to the installed capacity, from micro hydropower plants to hydroelectric power plants with an installed capacity of thousands of MW, such as Sanxia (Three Gorges Dam), Baihetan or Itaipu (Table 1).

Table 1. The ten largest hydropower plants by installed energy capacity

	Name	Installed capacity (MW)	Energy (GWh/year)	Country
1	Sanxia	22500	98100	China
2	Baihetan (under construction)	16000	51500	China
3	Itaipu	14000	98300	Paraguay/Brazil
4	Xiluodu	13860	57120	China
5	Belo Monte	11233	39500	Brazil
6	Guri	10235	53400	Venezuela
7	Tucurui	8370	41400	Brazil
8	Ta Sang (under construction)	7100	35440	Myanmar
9	Grand Coulee	6809	21000	United States of America
10	Grand Ethiopian Renaissance (under construction)	6420	16150	Ethiopia

Source: International Commission on Large Dams, 2020 (with some additions)

According to estimates by the International Commission on Large Dams (2020), there are over 58700 large dams worldwide with a cumulative water storage capacity of over 7700 km^3 (large dams are those that are over 15 m high or between 5 and 15 m height but with a water volume of over 3 million m^3). Of the 39110 dams analyzed by the International Commission on Large Dams, 28791 dams were designed for a single purpose (of which only 6115 are for electricity), and 10319 dams have multiple purposes (of which 4135 have an energy function). Along with these, another 3700 dams are under construction or are planned for construction worldwide, especially in developing economies (Zalf et al., 2015).

In 2020, the installed capacity of hydropower plants in the world reached 1330 GW, 1.6% more than in 2019 and more than double compared to 1995, when it was 625 GW (IHA, 2021; IRENA, 2021). This represents almost half of the total installed capacity of renewable energy (Figure 1). China ranks first in the world in total installed capacity, with over 370 GW, being the country with the largest contribution to the global growth of hydropower in recent decades. China is followed by Brazil, USA, Canada, India and Japan (Table 2). At the regional level, the largest installed capacity is in the Asia-Pacific region (656 GW), followed by Europe (254 GW), North and Central America (205 GW), South America (177 GW) and Africa (38 GW) (IHA, 2021).

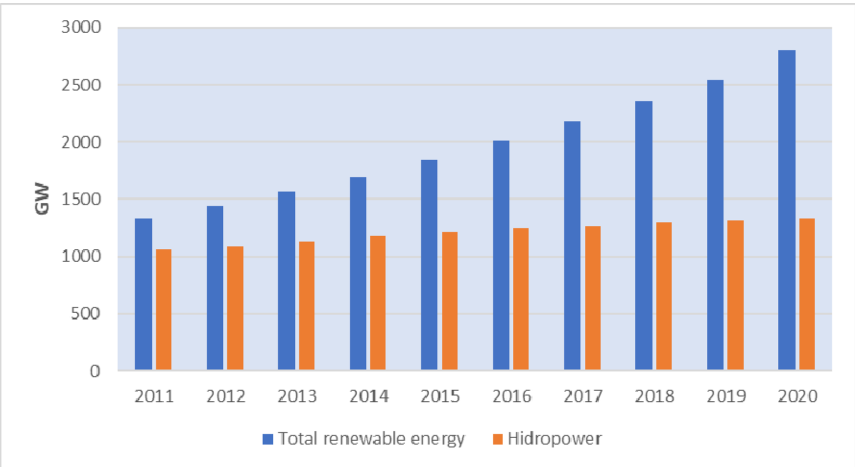

Figure 1. Hydropower capacity installed in relation to the total renewable energy capacity (Source: IRENA, 2021)

In 2020, hydropower plants generated about 4500 TWh of electricity. It is the third largest global source of electricity after coal and natural gas, but its contribution is 55% higher than that of nuclear energy and higher than that of all other renewable sources combined (IEA, 2021a). Although the total capacity of hydropower has increased over the last decade, its share of total production has remained relatively stable (16-17%), including due to the growth of other renewable energy sources, especially wind and solar photovoltaic energy (Figure 2).

Table 2. Largest hydropower producers and their installed hydropower capacity in 2020

		Installed capacity (GW)	**Electricity generation (TWh)**
1	China	370.2	1355.2
2	Brazil	109.3	409.5
3	United States	102	291
4	Canada	82	383
5	India	50.5	155
6	Japan	50	89.1
7	Russia	50	196
8	Norway	33	141.7
9	Turkey	31	77.4
10	France	25.5	64.8

Source: IHA, 2021

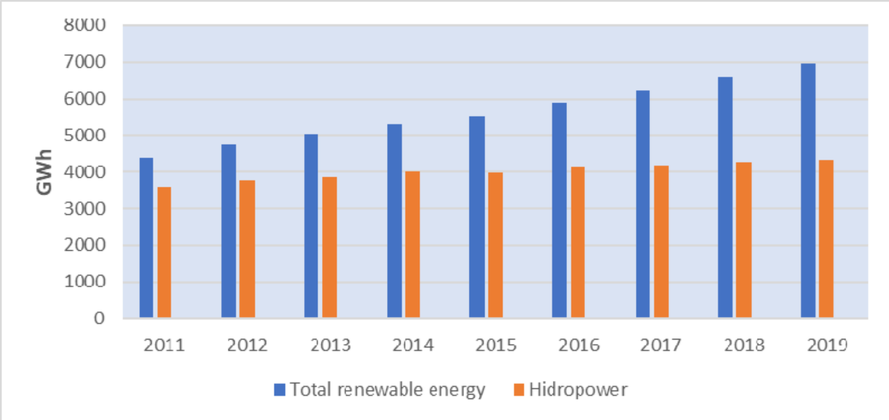

Figure 2. Hydropower production in relation to total renewable energy production (Source: IRENA, 2021)

In many parts of the world, especially in the developing world, hydropower supplies more than half of its electricity. In some cases, the share exceeds 90%: Albania, Bhutan, Central African Republic, Democratic Republic of Congo, Ethiopia, Kyrgyzstan, Lesotho, Namibia, Nepal, Norway, Paraguay and Tajikistan (Our World in Data, 2021).

4. Discussion

In the context of climate change, the contribution of hydropower plants to electricity production should increase significantly. To meet the goals of the Paris Agreement to limit global warming below 2°C above pre-industrial levels, IRENA (2020) stated in the Transforming Energy Scenario that a two-thirds increase in hydropower capacity by 2050 is needed compared to current levels. Thus, in the next three decades, approximately 850 GW of new installed capacity would be needed. Also, the International Energy Agency (2021c), in the Net Zero Emissions by 2050 Scenario, considers that in order to limit the increase in global temperature to 1.5°C, it is necessary to double the installed hydroelectric capacity by the middle of the century. To achieve this goal (net zero CO_2 emissions by 2050), an increase in installed capacity is needed on average by 2.3% per year. In the period 2016-2020, the average increase in installed capacity was about 1.8%, and in 2020 it was only 1.6% (IHA, 2021).

It is estimated that if the more than 3,700 major dams, each with a capacity of more than 1 MW, under construction (17%) or planned (83%) will be completed in the next three decades, the installed hydropower capacity would increase to approximately 1700 GW (Zalf et al. 2015). As many of these hydroelectric projects are located in developing countries, their construction is uncertain, especially due to the very high costs.

Major hydropower projects are very expensive and take a long time to complete. For example, the construction of the Itaipu Dam on the Parana River, on the border between Brazil and Paraguay, cost more than $ 17 billion and took about 10 years to start producing electricity in May 1984 (Itaipu Binacional, 2010). Also, the Inga 3 hydroelectric project in the Democratic Republic of Congo, announced in 2013 with the support of the World Bank at an estimated cost of $ 14 billion, has not yet begun (International Rivers, 2022). In general, the costs of a hydropower project range from less than $ 1000 / kW for very large plants to $ 10 000 / kW for small-scale projects (IEA, 2021a).

In addition to new hydropower projects, which would require investments of up to $ 1.7 trillion by 2050 (IRENA, 2020), significant investments are needed in modernizing obsolete hydropower plants. Almost 70% of North American hydropower plants and more than half of European hydropower plants are over 40 years old, with a global average age of 32 (IHA, 2021; IEA, 2021a). There are other factors that may influence the development of hydropower projects in the future.

Globally, about half of the hydropower potential is estimated to be untapped, especially in developing countries. In Africa, only about 10% of the potential is exploited, and there are also great opportunities for development in Asia or Latin America (Kumar et al., 2011). There is also the possibility of adding hydropower plants to the existing infrastructure. There are many dams, built for various uses (irrigation, flooding, navigation, etc.), which do not have power generation units.

On the other hand, most of the right locations have already been used. Compared to mountain dams, which can hold a large volume of water in a relatively small area, plains dams have reservoirs that usually occupy large areas of land. For example, the controversial Balbina hydroelectric plant, built on the Uatumă River to supply electricity to the Brazilian city of Manaus, flooded 2360 km^2 of the Amazon rainforest for an installed capacity of only 250 MW (Fearnside, 1989).

Although hydropower is a flexible source of energy, it still depends on certain climatic and hydrological features that cause rivers to flow, such as rainfall, temperature, or extreme weather events. The biggest problem that threatens the normal operation of hydropower plants is the increase in the frequency and duration of droughts in certain regions as a result of climate change. Droughts reduce the flow of rivers and the volume of water in reservoirs, significantly reducing electricity production. For example, Brazil has suffered from drought in recent years with the lowest levels of rainfall in the wet season (October to March) from record lows in 1991. The consequences of this are significant because the country relies on hydropower plants that generate more than 60% of the country's electricity.

The main problem of hydropower projects is the negative impact on the environment. Reservoirs, in some cases very large, flood extensive areas of land that include various ecosystems (forests, pastures or wetlands rich in biodiversity) and in some cases human settlements, agricultural land and cultural or historical sites. The Tanzanian government recently inaugurated the construction of Stiegler's Gorge dam on the Rufiji River in the Selous Game Reserve (a UNESCO World Heritage Site since 1982), one of the most iconic wildlife areas in Africa, relatively undisturbed by human activity (Lifegate, 2020).

According to International Rivers (2015), large hydropower projects have a serious impact on local communities and often violate the rights of indigenous peoples over their land, resources or cultural integrity. The dams displaced 40-80 million people and adversely affected about 472 million people living downstream. The opposition of dam-affected communities has often been met with flagrant human rights violations. Over time, many villages and towns were flooded and the inhabitants displaced, sometimes without their will. In 1982, about 400 people in Guatemala died and others were tortured for refusing to move from their homes to make way for the Chixoy Dam (The Guardian, 2012).

The worst effects of hydropower development on wildlife are the permanent loss of habitat by flooding, the introduction and spread of exotic species, and the obstruction of fish migration. Aquatic ecosystems downstream of the dam can also be affected by reducing the flow of water, sediment and nutrients. Sediments trapped behind dams may be essential for maintaining physical processes and habitats downstream of the dam, including deltaic or coastal areas. The erosion processes in the riverbed downstream of the dam can be significant.

The disruption of the natural flow of rivers alters water quality and disrupts the migration and reproduction of fish. Many fish species (such as salmon) depend on inland rivers for breeding, and dams prevent fish from reaching their spawning grounds. Reservoirs have different physical, chemical, and biological properties than river water, are often unsuitable for river dwellers, and sometimes host invasive species that affect native species. Higher reservoirs temperatures can cause algae to bloom and thus lower dissolved oxygen levels, which affects native fish species. Also, behind the dams accumulate large amounts of sediments and nutrients that can promote the development of algae and other aquatic plants.

Hydropower plants are not entirely environmentally friendly energy sources, being responsible for certain greenhouse gas emissions. These are emissions associated with the life cycle of hydropower plants and reservoirs. The decomposition of organic matter (especially of plant origin) in flooded areas, especially in hot and humid regions, leads to the release of substantial amounts of methane and carbon dioxide. Water plants, phytoplankton and algae take up CO_2 from the atmosphere as they grow, but after they die they settle to the bottom of the lake where they are digested by methane-producing microbes from sediments. Methane (CH_4) is a greenhouse gas that contributes significantly to global warming and its atmospheric concentrations have increased considerably in recent decades. There are also emissions produced during the construction of hydropower plants, especially dams, which require very large amounts of cement and steel.

In the case of hydropower plants in cold climates, greenhouse gas emissions are about 15 g CO_2/kWh equivalent, which is more than 30 times less than the emissions generated by fossil fuel thermal power plants (Gagnon and van de Vate, 1997). However, in the case of hydropower plants in tropical plains, such as the Amazon Plain, research shows that emissions from reservoirs can be very high, even exceeding fossil fuel plant emissions (Almeida et al., 2019). Most estimates of life cycle greenhouse gas emissions for hydropower are between 4 and 14 g CO_2/kWh equivalent (Kumar et al., 2011).

Even though dams are currently being built using best practices in the field, they are not entirely immune to threats, especially old dams. The destruction of dams as a result of natural disasters can have catastrophic effects on downstream regions. For example, in August 1975, Typhoon Nina struck the Chinese province of Henan and destroyed two large dams (Banqiao and Shimandan), two medium-sized dams and 58 small dams. The destruction of these dams has killed more than 26 000 people, flooded an area of about 12 000 km^2 and caused great economic losses (Xu et al., 2008). Over time, dams have caused other floods, with loss of life and material damage (U.S. Department of the Interior, 2015).

Due to the negative effects on the environment, hydropower developments have been heavily criticized, especially by environmental organizations such as American River or International Rivers. As a result of such pressures, in some cases, measures have been taken to remove dams to restore habitats. For example, in the Olympic National Park in Washington State the removal of two large dams on the Elwha River (Elwha Dam and Glines Canyon) was completed in 2014 (BBC, 2020). Also, after decades of controversy and campaigning by indigenous and environmental groups, four large hydroelectric dams on the Klamath River in northern California and southern Oregon will be removed after 2023, restoring hundreds of kilometers of habitat for salmon and other severely affected species. Eight dams were built on the Klamath River between 1900 and 1962 for hydroelectric power generation.

5. Conclusions

The prospect of severe effects of climate change on the environment requires an urgent shift to a low-emission greenhouse gas economy. This can be achieved by massive replacement of fossil fuels in the production of energy with renewable sources or low-carbon sources. Hydropower is currently the most important source of renewable energy and, due to its flexibility and relatively low production costs, is expected to play a significant role in the global energy sector in the coming decades.

Although globally only about half of the hydropower potential is exploited, the development of hydropower could be influenced by several factors. A first factor is that most hydropower projects are in the planning stage and belong to developing countries. Thus, their construction is not certain, especially due to the very high costs.

Another factor is the negative impact of hydropower projects on the environment, such as the loss of habitat by flooding or the prevention of fish migration. Hydropower plants are also responsible for certain greenhouse gas emissions, especially for tropical hydropower plants. Last but not least, hydropower depends on certain climatic and hydrological features, such as rainfall, temperature or extreme weather events, which could change in the future, and dams (especially old dams) can pose a threat to public safety.

The final conclusion is that hydropower is needed and should be developed. However, significant investments are needed to build new hydropower plants or to modernize existing ones, as well as certain compromises on environmental protection. In this regard, rigorous impact studies are required to minimize the environmental impact of hydropower projects.

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