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The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review

Luis Berga[a,b]

[a] International Commission on Large Dams, Paris 75116, France
[b] The Royal Academy of Sciences and Arts of Barcelona, Barcelona 08002, Spain

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ABSTRACT

Hydropower is a clean, renewable, and environmentally friendly source of energy. It produces 3930 (TW·h)·a^{-1}, and yields 16% of the world's generated electricity and about 78% of renewable electricity generation (in 2015). Hydropower and climate change show a double relationship. On the one hand, as an important renewable energy resource, hydropower contributes significantly to the avoidance of greenhouse gas (GHG) emissions and to the mitigation of global warming. On the other hand, climate change is likely to alter river discharge, impacting water availability and hydropower generation. Hydropower contributes significantly to the reduction of GHG emissions and to energy supply security. Compared with conventional coal power plants, hydropower prevents the emission of about 3 GT CO_2 per year, which represents about 9% of global annual CO_2 emissions. Hydropower projects may also have an enabling role beyond the electricity sector, as a financing instrument for multipurpose reservoirs and as an adaptive measure regarding the impacts of climate change on water resources, because regulated basins with large reservoir capacities are more resilient to water resource changes, less vulnerable to climate change, and act as a storage buffer against climate change. At the global level, the overall impact of climate change on existing hydropower generation may be expected to be small, or even slightly positive. However, there is the possibility of substantial variations across regions and even within countries. In conclusion, the general verdict on hydropower is that it is a cheap and mature technology that contributes significantly to climate change mitigation, and could play an important role in the climate change adaptation of water resource availability. However, careful attention is necessary to mitigate the substantial environmental and social costs. Roughly more than a terawatt of capacity could be added in upcoming decades.

1. Introduction

Electricity is essential for human life, welfare, and sustainable development. Images of the earth at night show the areas of prosperity—those people with access to electricity. However, about 20% of the world's population remains in the dark (with no access to lighting, refrigeration, computers, good education, or running water). Light means socioeconomic development, while darkness is a major concern for sustainable development. Today, more than 1.2 billion people around the world lack access to electricity, mainly in Asia and Africa (about 80% are in rural areas) [1]. Socioeconomic analyses on electricity and development are based on correlations between the main electricity indicators (i.e., consumption per capita per year, kW·h per year per capita, and the percentage of the population with access to electricity (AE%)) and the macro-socioeconomic indicators (i.e., gross national income (GNI) per capita and human development index (HDI)). All socioeconomic analyses show that in developed countries (those with high income (HI) and a high HDI), 100% of the population has access to electricity, and the average consumption is about 8500 kW·h per year per capita. In contrast, in countries with low income and low HDI, only about 25% of the population has access

E-mail address: lubergc@telefonica.net

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to electricity, and the consumption is less than 500 kW·h per year per capita. Thus, there is a strong correlation between electricity indicators and socioeconomic development [2].

Currently, humanity faces the challenge of reaching the new Sustainable Development Goals (SDGs) by 2030. These goals are a sustainable development agenda to guide development actions for the next 15 years. They include 17 goals and 169 targets, and require an annual investment evaluated at 3.3 trillion–4.5 trillion US dollars per year. Energy-related challenges are in Goal 7, which has the aim of ensuring access to affordable, reliable, sustainable, and modern energy for all. Goal 7 has four targets to be met by 2030; these focus mainly on ensuring universal access to energy, increasing the share of renewable energy in the global energy mix, improving energy efficiency, and expanding infrastructure and upgrading technology for supplying modern and sustainable energy [3–5].

2. Electricity and climate change

Greenhouse gas (GHG) emissions due to human activity have been altering the energy and climatic patterns of our planet. The main gas involved is carbon dioxide (CO_2), which represents 76% of total GHG emissions. These emissions have increased the atmospheric concentration of CO_2 from ~277 ppm in 1750 to 397 ppm in 2014, an increment of about 43%. In 2015, CO_2 levels registered several peaks over 400 ppm in March and December. In relation to economic activities, the burning of coal, natural gas, and oil for electricity and heat is the largest single source of global GHG emissions.

The international political response to global GHG emissions and climate change began in 1992 with the constitution of the United Nations Framework Convention on Climate Change (UNFCCC), which set out a legal framework for stabilizing atmospheric concentrations of GHGs in order to avoid dangerous anthropogenic interference with the climate system. After many annual meetings, with advances and failures, the 21st session of the Conference of the Parties (COP21) occurred in Paris from November 30 to December 11, 2015. The Paris meeting was a world-leading event that brought together over 150 heads of state and governments to generate political will toward an agreement. The conference brought together over 36 000 participants; nearly 23 100 government officials; 9400 representatives from United Nations (UN) bodies and agencies, intergovernmental organizations, and civil society organizations; and 3700 members of the media.

In Paris, parties agreed to limit the increase in global average temperature to well below 2 °C above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that such a limitation would significantly reduce the risks and impacts of climate change. Each party is required to—shall prepare, communicate, and maintain successive Intended Nationally Determined Contributions (INDCs) for themselves to achieve. Countries must make a progressive voluntary pledge, one that is not fully binding, of mitigation efforts of GHG emissions. This is the first global agreement to mitigate climate change that includes all the countries in the world, and is a first keystone step [6]. However, the INDCs that have been provided to date by most countries only extend to the year 2030, and would suppose an increase in temperature of about 3 °C to 3.5 °C—far greater than the proposed scenario of 2 °C and 450 ppm of CO_2. Therefore, it will be necessary for countries to make promises and additional efforts regarding GHG emissions after the year 2030 [7].

The UNFCCC is under way to reach global agreement on the reduction of GHG emissions. Moreover, there is a general consensus on key points regarding the mitigation of electricity-related emissions. These key points include: the important development of renewable energy—that is, solar, wind, geothermal, bioenergy (green power), and hydropower (blue power); an improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; combined heat and power; and early applications of CO_2 capture. In addition, the approved COP21 Paris Agreement acknowledges the need to promote universal access to sustainable energy in developing countries, and particularly in Africa, through the enhanced deployment of renewable energy.

3. Hydropower and climate change

Hydropower is a clean, renewable, and environmentally friendly source of energy, which produces an average of 3930 $(TW·h)·a^{-1}$ and yields 16% of the world's generated electricity, representing 78% of renewable electricity generation in 2015 (Fig. 1). Global hydro capacity is 1100 GW (mainly in Asia and Latin America), and has increased at a compound annual rate of about 3.5% over the last five years. About 160 GW of hydro capacity are currently under construction, and more than 1000 MW are planned.

There are currently about 1200 large dams under construction in 49 countries around the world, mainly in Asia. Of these, 347 are major dams (with a height over 60 m) located in 49 countries. For the majority of these major dams (202, or 58%), hydropower is one of the main objectives, and more than 50% are multipurpose reservoirs [8].

Hydropower has been extensively implemented in developed countries, which have tapped more than 50% of their technical feasible potential. Although emergent economies have developed between 20% and 30% of their hydropower potential, developing countries have a large remaining hydro potential. Africa is an extreme case, where only 7% of economically feasible hydropower potential has been developed (Fig. 2). In general, developed countries have already exploited much of their hydropower potential, while emergent and developing countries still have a long way to go [1].

Hydropower and climate change show a double relationship. On the one hand, hydropower is an important renewable energy resource that contributes significantly to the avoidance of GHG emissions and the mitigation of global warming. On the other hand, it is likely that climate change will alter river discharge, resulting in impacts on water availability, water regularity, and hydropower generation [9].

3.1. The role of hydropower in climate change mitigation

Renewable energy technologies, such as hydropower, contribute significantly to the reduction of GHG emissions and to the security of the energy supply. In comparison with conventional

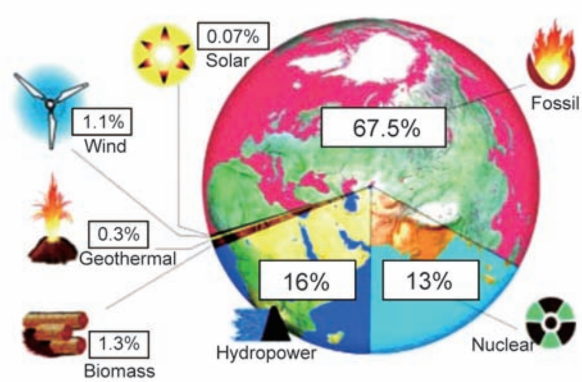

Fig. 1. Main sources of electricity generation in 2015.

coal power plants, hydropower prevents the emission of about 3 GT CO_2 per year, or about 9% of global annual CO_2 emissions. In general, hydropower is a source of energy that produces few GHG emissions. According to the World Energy Council (WEC), the CO_2 emissions per GW·h are 3–4 t for hydropower run-of the river, and 10–33 t for hydropower with a reservoir; these values are about 100 times less than the emissions from traditional thermal power [10]. In addition, the SRREN (2011), which is a special report of the International Panel on Climate Change (IPCC) titled "Renewable Energy Sources and Climate Change Mitigation," shows that the majority of lifecycle GHG emission estimates for hydropower cluster are between 4 and 14 g CO_2 eq·$(kW·h)^{-1}$, as shown in Fig. 3 [11]. Under certain scenarios, however, the potential exists for much larger quantities of GHG emissions from hydropower, as shown by some outliers—although these quantities are always much lower than those from thermal power [11]. During the last decade, there has been a debate on the methodologies and reliability of determining GHG emissions from hydropower reservoirs. Long scientific controversies have occurred regarding reservoirs' GHG emissions and, in some cases, uncertainty and exaggerations have discredited hydropower development. For example, a few early estimates from the year 2000 rank hydropower emissions as high as 7% of all global emissions. To spread the current state of the art, the World Bank published an interim technical note titled "Greenhouse gases from reservoirs caused by biochemical processes" in April 2013. The main purposes of this note were to clarify the confusion around GHG emissions from reservoirs and to give concrete guidelines on how GHGs from reservoirs can be studied within the environmental impact assessment (EIA) process. The main conclusions were that the perception that reservoirs emit high levels of GHGs largely stems from older studies that were mainly conducted at sites with very unfavorable conditions. GHG emissions seem to be relatively small for an overwhelming majority of reservoirs [12].

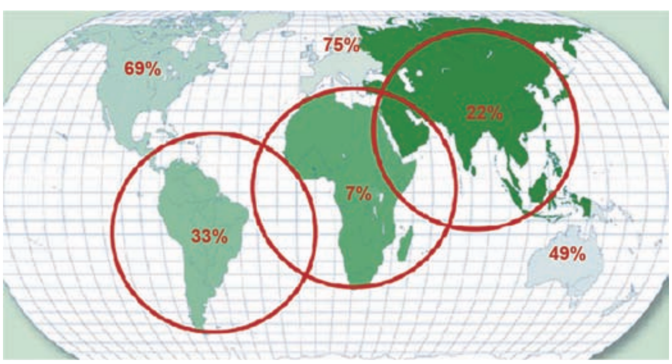

Fig. 2. Hydropower undeveloped technical potential.

Hydropower is the cheapest renewable energy source and is often economically competitive with current market energy prices. It requires relatively high initial investment, but has a long lifespan with very low operation and maintenance costs. The levelized cost of electricity for hydropower projects spans a wide range but, under good conditions, can be as low as 3 to 5 US cents per kW·h (in 2005) [11]. Another advantage of hydropower is that it has one of the best conversion efficiencies of all known energy sources (about 90% efficiency, water to wire). Hydropower also shows high reliability, flexibility, and variety in project scales and sizes, which gives it the ability to meet large centralized urban and industrial needs as well as decentralized rural needs.

In the last decade, hydropower, wind energy, and solar energy have been developed strongly, with a spectacular increment of renewable energy. The period from 2004 to 2013 saw an increase of about 760 GW in renewable energies (37.5% hydropower, 35.5% wind, and about 18% solar photovoltaic), as shown in Fig. 4 [13]. In addition, particular, hydropower has a timely synergy with other renewable energy sources. Hydropower, wind energy, and solar energy should be contemplated in an integrated way, with a holistic vision, within the future electric mix. These three resources present important synergies, as wind and solar energies are intermittent and very variable, while hydropower is able to balance out variability and supply the peak load. In addition, hydropower is the only system that currently exists to store energy in a significant and effective way, in the form of pumped storage power plants, which make up 97.5% of global energy storage in the electricity networks [14].

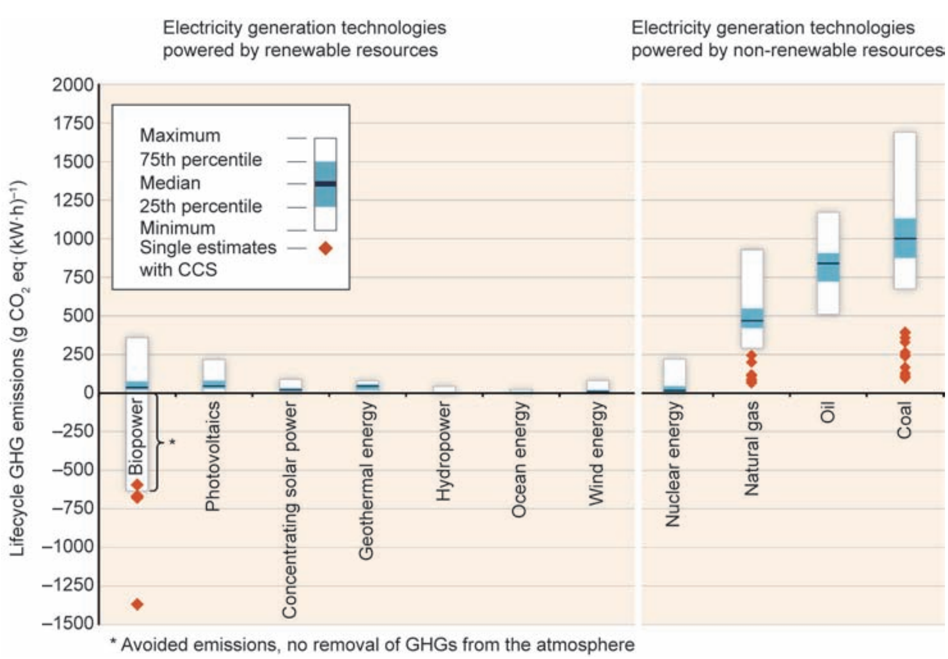

Fig. 3. Lifecycle greenhouse gas (GHG) emissions of electricity generation technologies powered by renewable and non-renewable resources [11].

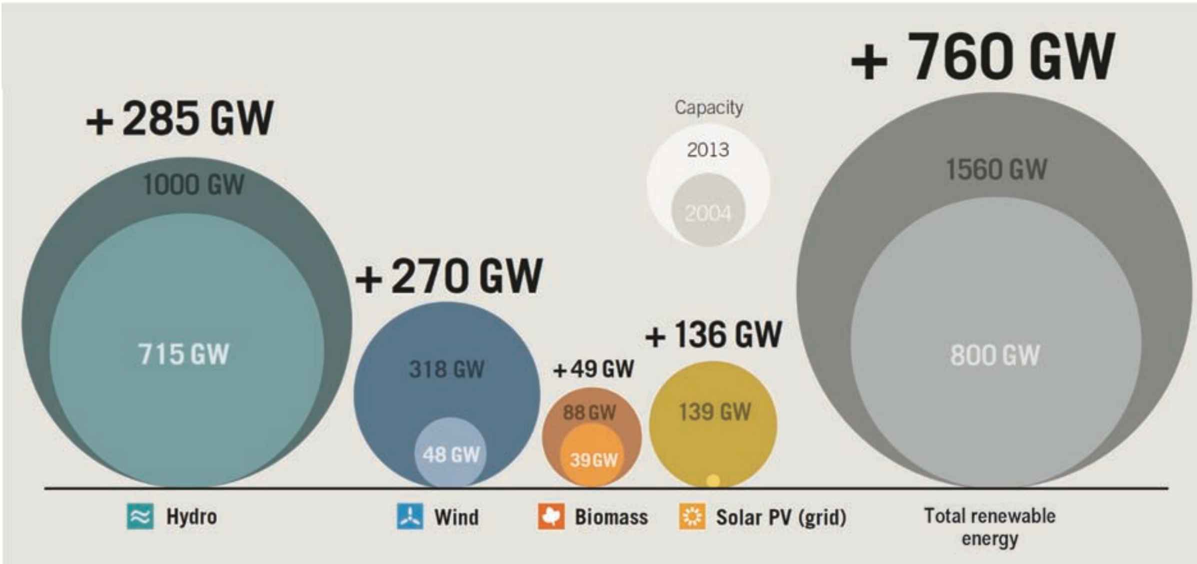

Fig. 4. New renewable power capacity additions by technology from 2004 to 2013 [13]. Geothermal figures for 2004 and 2013 were 9 GW and 12 GW, respectively. For concentrating solar power (CSP), capacity was 0.4 GW in 2004 and 3.4 GW in 2013. These amounts have been included in the "Total renewable energy" calculation.

3.2. The role of hydropower storage in climate change adaptation

Climate change is producing a warmer world, leading to an increase in sea level and a decrease in snow cover. It is likely that the temperature increase due to climate change will interact with the hydrological cycle, resulting in changes in precipitation, evapotranspiration, and soil moisture; melting glacier ice and ice caps; and river flow variability. These changes will have impacts on water resources and water supply, floods and droughts, and hydropower generation. The projected changes described in the Fifth Assessment Report (AR5) of IPCC include an increase in water resources at high latitudes, in tropical East Africa, and in Southeast Asia, and a decrease of water resources in many semi-arid and arid areas (e.g., the Mediterranean Basin, Western US, Southern Africa, and Northeastern Brazil). Runoff will be notably reduced in Southern Europe [15]. In the future, these projected impacts of climate change on water resources could suppose a major time irregularity, an uneven geographical distribution of water resources, and a seasonal shift in streamflow in glaciers and snow-fed rivers. Accessibility to water resources could then decrease, causing major water scarcity in the more water-stressed countries of the world. In this context, it is necessary to remark that in relation to the storage (i.e., dams and reservoirs) and availability of water resources, sensitivity analyses to climate change in regulated basins show that regulated basins with a large reservoir capacity are more resilient to water resource changes than unregulated basins and less vulnerable to climate change, and that the water storage acts as a buffer against climate change [3]. Therefore, given the current circumstances and the need for responsible development in the contexts of a changing world and climate change, increasing water storage capacities is a major imperative. Investments in climate change adaptation should incorporate water storage [4]. One of the challenges is to promote multipurpose dams and better planning tools for multipurpose water projects. Hydropower storage capacity can provide security for irrigation, drinking water supply, flood control, and navigation services, in the framework of Integrated Water Resources Management (IWRM). Hydropower storage in multipurpose dams will contribute to climate change adaptation by maintaining the availability of water resources. Multipurpose hydropower projects may have an enabling role beyond the electricity sector, as a financing instrument for multipurpose reservoirs [11,16].

3.3. Impacts of climate change on hydropower generation

It is likely that climate change will alter river flow variations and discharges, resulting in impacts on hydropower generation. In general, the impacts of climate change on hydropower generation could be very variable and locally different, depending on changes in the flow regimes and on the effects of glaciers and snow melting. For example, hydropower potential for the whole of Europe has been estimated to potentially decline by 6% by the 2070s. A 15% to 30% increase has been estimated for Northern and Eastern Europe, a stable hydropower pattern is projected for Western and Central Europe, and a 20% to 50% decrease is expected around the Mediterranean [17]. At the global level, the IPCC SRREN concludes that the overall impacts of climate change on existing hydropower generation may be expected to be small, or even slightly positive. However, results also indicate the possibility of substantial variation across regions and even within countries, as shown in Table 1 [11].

It is important to remark that these future projections carry a

Table 1
Power generation capacity in 2005, and estimated changes due to climate change in % ((TW·h)·a^{-1}) in 2050 (SRES A1B [11]).

	Power generation capacity (2005)		Change by 2050 (TW·h)·a^{-1} (PJ·a^{-1})
	GW	(TW·h)·a^{-1} (PJ·a^{-1})	
Africa	22	90 (324)	0.0 (0)
Asia	246	996 (3 586)	2.7 (9.7)
Europe	177	517 (1 861)	−0.8 (−2.9)
North America	161	655 (2 358)	0.3 (≈ 1)
South America	119	661 (2 380)	0.3 (≈ 1)
Oceania	13	40 (144)	0.0 (0)
Total	737	2 931 (10 552)	2.5 (9)

SRES is short for Special Report on Emissions Scenarios, which is a report by the Intergovernmental Panel on Climate Change (IPCC); A1B stands for "a balanced emphasis on all energy sources," which is one of the SRES scenarios.

high level of uncertainty. Uncertainty in socioeconomic scenarios and in the grade of projections of the models shows major contradictions in some regions. Climate change poses a conceptual challenge to water and hydropower managers by introducing uncertainty in future hydrological conditions. The projections cannot provide decision makers with exact information on the rate of future changes, but they can offer very useful general information, and can serve as a preliminary and initial assessment. It is essential that data, trends, and projections on hydropower generation should be well-monitored and analyzed closely in the future, in order to implement a well-informed adaptive management [1].

4. Trends in hydropower development

The evolution of hydropower generation shows an increased development from the beginning of the 21st century (Fig. 5) [18].

In addition, the trends for upcoming decades foresee a great expansion of hydropower. The projection of the number of hydropower plants with a capacity greater than 1 MW shows a total of 3700 hydro projects in 102 countries around the world by 2030. Of these, 629 (17%) are under construction and 3071 (83%) are planned, mainly in developing countries and emergent economies in Asia, South America, Europe (Balkans, Anatolia, and the Caucasus), and Africa (Fig. 6 [19]). The estimated investment is about 2000 billion US dollars [19].

The total installed capacity of these hydropower projects will reach about 700 GW. Although the small and medium sized (1–100 MW) projects are greater in number (> 76% of all the dams), 92% of the capacity will be in 812 large (> 100 MW) projects, as shown in Fig. 7.

Hydropower development has a very important role in future mitigation scenarios of climatic change. In the International Energy Agency (IEA) scenario of an emissions peak at 450 ppm with a maximum increment in temperature of 2 °C, which is the generally accepted scenario, the capacity of hydropower generation should increase 70% by 2030, and 100% by 2050 [20]. More recently, the International Renewable Energy Agency (IRENA)'s global Renewable Energy Roadmap (REMAP 2030), in line with the UN Secretary-General "Sustainable Energy for All" (SE4ALL) scenario, which aims to double the global share of renewable energy as described in "Doubling the Global Share of Renewable Energy: A Road Map to 2030," requires around 2200 GW of total hydropower capacity to achieve its targets. This assumes an additional 500 GW of hydropower capacity to be built, in addition to the IEA projections [21].

5. Conclusions

Hydropower is a clean, renewable, and environmentally friendly source of energy, which yields 16% of the world's generated electricity and about 78% of renewable electricity generation (in 2015). It contributes significantly to the reduction of GHG emissions and to the security of the energy supply. In comparison with conventional coal power plants, hydropower prevents the emission of about 3 GT CO_2 per year, or about 9% of global annual CO_2 emissions. In general, it is a source of energy that produces few GHG emissions.

Another advantage of hydropower is that it is one of the cheapest renewable energy sources, and is often economically competitive with current market energy prices. It requires relatively high initial investment, but has a long lifespan with very low operation and maintenance costs. Hydropower has among the best conversion efficiencies of all known energy sources (about 90% efficiency, water to wire). In addition, it shows high reliability, flexibility, and variety in project scales and sizes, which

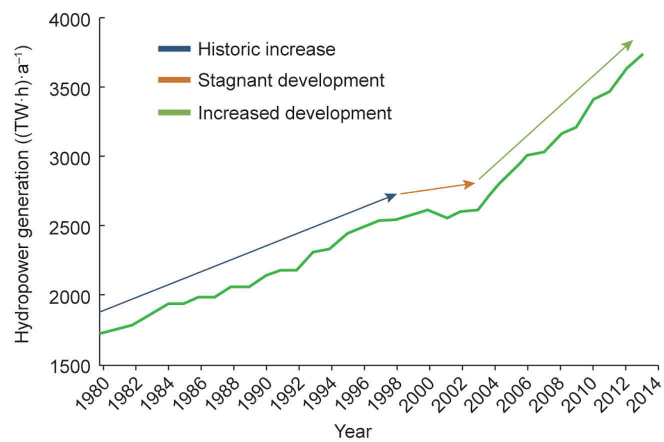

Fig. 5. The evolution of world hydropower generation since 1980 [18]. Source: International Hydropower Association (IHA), US Energy Information Administration (EIA), Renewable Energy Policy Network for the 21st Century (REN21)—Renewables 2014 Global Status Report.

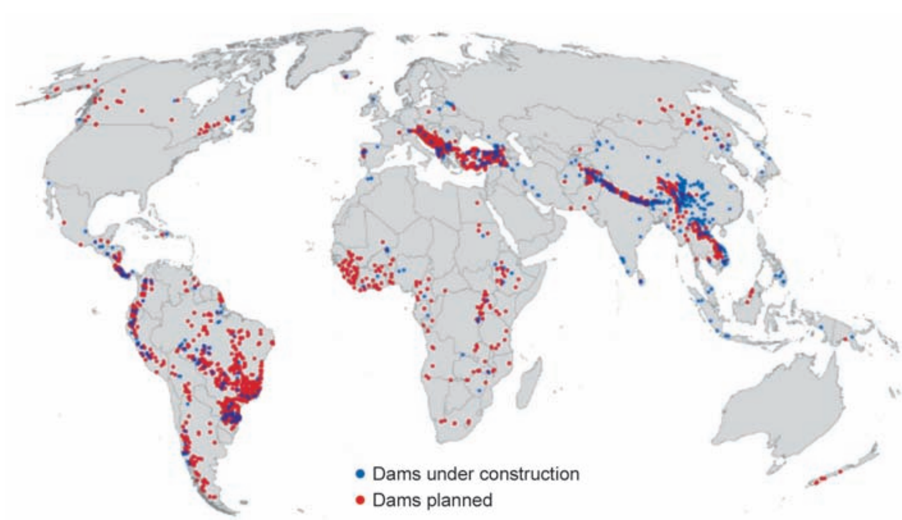

Fig. 6. Location map of hydropower dams under construction and planned by 2030 [19].

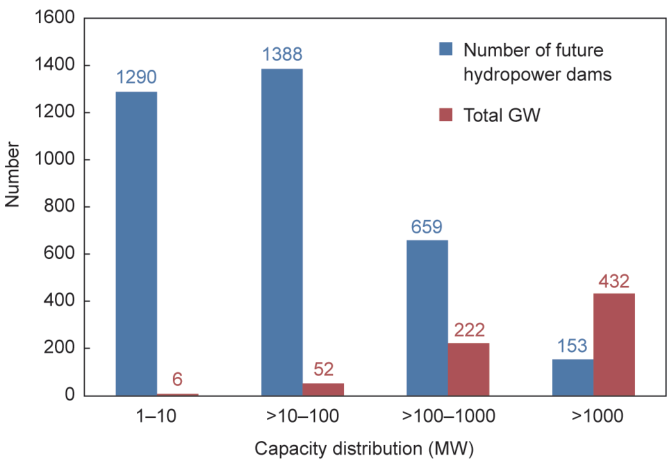

Fig. 7. Number and capacity distribution of future hydropower dams.

gives hydropower the ability to meet large centralized urban and industrial needs as well as decentralized rural needs.

Hydropower, wind energy, and solar energy have important synergies, because wind and solar energies are intermittent and very variable, while hydropower is able to balance out variability and supply the peak load. In addition, hydropower is the only system that currently exists to store energy in a significant and effective way—in pumped storage power plants, which provide 97.5% of global energy storage in the electricity networks.

Hydropower generation has shown increased development from the beginning of the 21st century. Trends for upcoming decades foresee a great expansion of hydropower, mainly in developing countries and emergent economies. In climate change mitigation scenarios, hydropower development has a very important role. The last IRENA REMAP 2030 scenario, which aims at doubling the global share of renewable energy, requires 2200 GW of global hydropower capacity to achieve its targets.

In conclusion, the general verdict on hydropower is that it is a cheap and mature technology that contributes significantly to climate change mitigation, and could play an important role in climate change adaptation regarding the availability of water resources. However, careful attention is required to mitigate hydropower's substantial environmental and social costs. Roughly a terawatt of capacity could be added in upcoming decades.

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