GREENHOUSE GAS AND OTHER ENVIRONMENTAL, SOCIAL, AND ECONOMIC IMPACTS OF HYDROPOWER: A LITERATURE REVIEW

CLIMATE ECONOMIC ANALYSIS FOR DEVELOPMENT, INVESTMENT, AND RESILIENCE (CEADIR)

March 13, 2019

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Front photo source: Itaipu Dam in Brazil, taken by International Hydropower Association on July 8, 2011, https://upload.wikimedia.org/wikipedia/commons/8/8e/Itaipu_Aerea.jpg

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ACRONYMS AND ABBREVIATIONS

ASCE	American Society of Civil Engineers
BNEF	Bloomberg New Energy Finance
CDM	Clean Development Mechanism
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CTL	Coal to liquids
DEG	German Investment Corporation
EPA	Environmental Protection Agency
FMO	Netherlands Development Finance Company
GENISA	Generadora del Istmo S.A.
GHG	Greenhouse gas
GW	Gigawatt (10^9 watts)
GWh	Gigawatt-hour
GWP	Global warming potential (relative to carbon dioxide)
HSAP	Hydropower Sustainability Assessment Protocol
ICOLD	International Commission on Large Dams
IEA	International Energy Agency
IFC	International Finance Corporation
IMF	International Monetary Fund
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IUCN	International Union for Conservation of Nature
KWh	Kilowatt-hour
Km	Kilometer
Km^2	Square kilometers
LACE	Levelized avoided cost of electricity
LCA	Life cycle assessment
LCOE	Levelized cost of electricity
LMB	Lower Mekong Basin
M^2	Square meter
M^3	Cubic meters
MRC	Mekong River Commission
MW	Megawatts (10^6 watts)
MWh	Megawatt-hour
N2O	Nitrous oxide
NGO	Nongovernmental organization
NREL	National Renewable Energy Laboratory
NPV	Net present value
PV	Photovoltaics
REN21	Renewable Energy Policy Network for the 21st Century
T	Metric tons
Tg	Teragram (10^6 metric tons)
tCO_2e	Metric tons of carbon dioxide equivalent
TWh	Terawatt-hours

UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USEIA	United States Energy Information Administration
USEPA	United States Environmental Protection Agency
W	Watt
W/m^2	Watt per square meter
WCD	World Commission on Dams

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EXECUTIVE SUMMARY

This review addresses several categories of information about hydropower dams to provide a comprehensive review of current literature on the greenhouse gas (GHG), environmental, and social and cultural impacts of hydropower dams as well as the financial and economic benefits and costs. In section 2, we discuss the direct and indirect greenhouse gas impacts of hydropower dams and compare them to other power generation technologies. In section 3 we discuss the other environmental and social impacts of hydropower dams. Finally, in section 4 we discuss the financial and economic benefits and costs of hydropower dams. The intention of these categories is to provide a practical and comprehensive discussion of the state-of-the-knowledge of the impacts of hydropower dams.

Hydropower dams have direct and indirect effects on emissions of greenhouse gases that contribute to global warming. Based on the full range of studies available, it appears likely that hydropower reservoir dams *typically* have far lower life cycle GHG emissions than coal, petroleum, or natural gas thermal power plants and similar life cycle GHG emissions to nuclear, photovoltaics, and wind power systems. However, there is still tremendous uncertainty about the direct and indirect GHG emissions from hydropower, and there are some notable examples of hydropower systems that have emissions as high or higher than fossil fuel powered thermal power plants, suggesting that significant care needs to be exercised in the location and design of hydropower dams to ensure lower life cycle GHG emissions.

There is a large range in the life cycle GHG emissions from hydropower. Characteristics of hydropower dams that are positively correlated with GHG emissions include location in the tropics, quantity of biomass flooded, reservoir age below 15 years, high water temperatures, eutrophic river systems with high nutrient loadings, and shallow reservoir depth. Typically, the most important drivers of the lifecycle GHG emissions from hydropower are reservoir size and climatic zone. Large, shallow hydropower reservoirs in the tropics generally had the highest measured GHG emissions, but more research is needed in other locations.

The risks of high GHG emissions from hydropower reservoirs can be reduced by:

- Ensuring a high power density, preferably greater than 1 watt per square meter (W/m^2) of reservoir surface area;
- Minimizing the inundated area and removing terrestrial biomass before inundation;
- Siting nutrient sources upstream from reservoirs and implementing nutrient reduction strategies;
- Incorporating design features, equipment, and operating measures to reduce CH_4 emissions from degassing of turbines and emissions downstream of the impoundment (including drawing water for the turbines close to the reservoir surface); and
- Re-engineering old reservoirs to increase power production, for example, through sediment removal;
- Decommissioning reservoirs with declining power output that cannot be improved.

In addition to GHG impacts, dams have important environmental and social and cultural impacts that should be considered in any review of hydropower dams. These impacts vary considerably by location, prior land cover, climatic zone, age, size, and type of hydropower facility, proximity of human settlements, and the need to relocate populations.

Other environmental impacts of hydropower systems include alteration of flow regimes, changes in water quality, lower fish populations and fish diversity, and flooding of habitat that reduces terrestrial

biodiversity. Displacement of people during dam establishment is a major social impact of hydropower, with particularly harmful effects on indigenous groups, marginalized populations, and women. Displacement can lead to unemployment and underemployment, loss of access to key resources, reduced income from farming, disruption of social and community networks, and public health risks. Adequate compensation in cash or in kind has rarely been offered to displaced people. Other concerns from hydropower dams include dam safety and disease vector breeding.

Despite the site specificity of the impacts and research gaps, there are some general principles for reducing the negative environmental and social impacts of dams. Protocols, assessment tools, and standards have been developed to assess and reduce or mitigate the negative environmental and social impacts of large-scale hydropower. However, none of the protocols and assessment tools are broadly acceptable to key stakeholders and most have not been widely used yet. Some multilateral development banks have recently improved their standards for environmental and social safeguards for the hydropower investments that they finance.

It is also important to identify the financial and economic benefits and costs of hydropower. New hydroelectric power investments can support national and subnational economic development and energy self-sufficiency or exports. Increased employment from large dam construction can continue for a decade or longer. Hydropower dams can also increase economic production from irrigated agriculture, aquaculture, and reservoir-based fisheries for greater food security and rural poverty reduction. Reservoir dams can manage a river's flow, capture heavy rainfall to mitigate drought, and reduce flooding. They can also provide water for irrigation and human and animal consumption.

Hydropower has some advantages as a source of electricity. It has good black-start capability to supply power after a blackout at lower cost than coal or natural gas turbines. It can balance electricity demand and supply from variable or intermittent renewable energy sources and help meet peak loads. Smaller pumped storage dams can reduce the need for new power generation capacity, but may become less competitive in the future as battery storage costs continue to decline.

The actual financial and economic viability of large-scale hydropower has often been below projections. The economic costs of hydropower have often been underestimated or reduced by subsidies and the economic benefits have often been overestimated. In addition, the environmental and social costs have generally not been valued at all. Capital costs tend to increase with dam scale and height, but power generation capacity also increases with dam size. As a result, there is not a strong correlation between the scale of a hydropower dam and the cost per unit of electricity generated. Due to the long time required for planning, siting, and construction, large-scale hydropower is not a short-term solution for an increasing demand for electricity. In addition, lengthy delays in completion are common and increase cost over-runs.

Previously, financial and economic analyses of hydropower rarely considered sediment management costs to extend the useful life of reservoirs. As a result, sedimentation has reduced the benefits of large-scale hydropower dams by decreasing the life and capacity factor of the reservoir and turbines. Severe droughts have also kept many dams from achieving their planned electric power generation rates.

1. INTRODUCTION

This literature review summarizes the greenhouse gas (GHG) emissions, other environmental, and social and cultural impacts of hydropower that should be considered in planning, construction, and operation of hydropower dams. It also describes the financial and economic benefits and costs of hydropower. This review focuses on hydropower systems with a primary purpose of electricity generation.

Box 1 contains definitions of three types of hydropower systems included in this assessment: reservoir dams, run-of-river systems, and pumped storage. The economic, environmental, and social impacts of hydropower vary considerably by type, size, and location, but the literature on the impacts of hydropower is often unclear on these distinctions.

BOX 1. Types of Hydropower Dams

Reservoir dams: An impoundment is built to hold standing water. The stored water is run through turbines that activate a generator to produce electricity. This is the most common source of hydropower. Hydropower dams may also serve other purposes besides power generation, such as providing irrigation water in dry seasons and controlling downstream flooding in rainy seasons.

Run-of-river systems: These units channel part of a river's water through a canal or penstock to generate electricity. If there is a dam in a run-of-river system, it provides little or no storage. As a result, the amount of electricity generated varies with the river level and may only be intermittent.

Pumped storage dams: Pumped storage dams use surplus electric power to move water to higher elevations when there is surplus electricity that either cannot be sold at all or can only be sold at a low or even negative price. When the power load increases or prices rise, the pumped water is released to flow down through the turbines to generate additional electricity. Although pumping water uphill consumes electricity, it increases the value of the electricity that is sold.

Worldwide, hydropower capacity reached 1,114 gigawatts (GW) in 2017, a 1.7 percent increase over the previous year. In decreasing order, the countries with the most hydropower capacity in 2017 were China, Brazil, Canada, the United States, Russia, India, Norway, Turkey, Japan, and France. Excluding pumped storage, hydropower comprised 11 percent of the new renewable energy capacity in 2017 (compared to 55 percent for solar power and 29 percent for wind power). Renewable energy accounted for 70 percent of the net additions to global power capacity in 2017.

Total hydropower generation in 2017 was 4,185 terawatt-hours (TWh), excluding pumped storage. This comprised 16.4 percent of world electricity generation, a 2 percent increase over the previous year. Hydropower generation varies each year with the available capacity, weather and hydrological conditions, electricity demand, the demand for other uses of the water in reservoirs, and the price and availability of competing sources of electricity.

In 2017, $45 billion in new asset financing was obtained for large-scale hydropower with a capacity of over 50 MW. In addition, $3 billion was raised for small-scale hydropower. The total hydropower investment of $48 billion was double the amount in 2016. However, $28 billion of the total was for one system, the 16 GW Baihetan Project on the Jinshan River in China, which is expected to be the second largest hydropower facility in the world when completed in 2022. In comparison, the total new investment in renewable electric power capacity was $276.8 billion in 2017 (mainly solar and wind power), up 2 percent over the previous year despite lower unit costs of wind and solar capacity.

Renewable power capacity, including large- and small-scale hydropower, received triple the new investment in fossil fuel generation capacity and more than double the total for fossil fuel and nuclear power plants. In decreasing order, the largest new investments in hydropower in 2017 were in China, Brazil, India, Angola, Turkey, Iran, Vietnam, Russia, Sudan, and Cote d'Ivoire (Renewable Energy Policy Network for the 21st Century (REN21) 2018a).

The trend in hydropower investment is lower than in 2005-2013 and. Bloomberg New Energy Finance (BNEF) sees little sign of resurgence in 2018. The potential for additional hydropower capacity is 2000–2050 GW of installed hydropower capacity by 2050 (World Energy Council 2016b). Most of the additional potential is in developing regions — 48 percent in Asia, 19 percent in South America, and 15 percent in Africa (Hoes *et al*. 2017). BNEF projected that $911 billion would be invested in hydropower out of the total investment of $7.8 trillion for renewable energy between 2016 and 2040 (BNEF 2016). However, the share of electricity generation from hydropower may decrease from 17 percent to 9 percent by 2050 as photovoltaic and wind power generation increase (BNEF 2018).

Hydropower is a mature technology that can have a long life — 30-40 years for electro-mechanical equipment and 40-80 years or more for dam structures. Hydropower dams can also provide other services besides electricity, such as irrigation, drinking water supply, flood control, navigation, fishing, and recreation. Hydropower can increase the usability of variable, renewable energy sources on electric grid by balancing the intermittency of supply.

It appears likely that hydropower generally produces fewer GHG emissions than thermal electricity from fossil fuel sources. However, there is increasing scientific information that hydropower development and operations can have substantial GHG emissions when changes in land use and water systems are taken into account.

There is still considerable uncertainty about the relationships between dam and site attributes and GHG emissions. Over the last decade, some research has been conducted on the GHG emissions from hydropower dams in the tropics, but there is still limited information on the GHG impacts under different conditions and locations. In particular, there is insufficient information on the net GHG emissions from clearing trees and other vegetation and construction and operation of the reservoir and turbines. The GHG emissions can be reduced somewhat with good practices for designing and operating dams.

Climate can also have a major effect on the technical potential and financial and economic viability of hydropower. *Technical potential* is the portion of the theoretical resource that can be captured; it does not consider policy goals, costs, social acceptability, or environmental damage.

2. GHG IMPACTS OF HYDROPOWER

Hydropower dams have direct and indirect effects on emissions of several greenhouse gases that may contribute to global warming, but it seems likely that the emissions are generally, but not always, lower than from fossil fuel (thermal) power plants. Run-of-river hydropower has lower GHG emissions than dams. Hydropower dams also have other environmental and social impacts that vary considerably by location, prior land cover, climatic zone, age, size, and type of hydropower facility, proximity of human settlements, and the need to relocate populations. Despite the site specificity of the impacts and research gaps, there are some general principles for reducing the negative environmental and social impacts of dams.

The various types of GHGs differ in their ability to absorb energy (*radiative efficiency*), and persistence in the atmosphere (*lifetime*). By definition, carbon dioxide has a global warming potential (GWP) of one as it is the basis for comparing other greenhouse gases. CO_2 emissions can remain in the atmosphere for thousands of years. Methane (CH_4) has a higher radiative efficiency, but shorter lifetime than carbon dioxide. The GWP of methane is 28-36 times that of CO_2 over 100 years and 84-87 times as much over 20-years. Nitrous oxide (N_2O) has a GWP 265–298 times that of CO_2 over a 100-year period and can remain in the atmosphere for more than 100 years (USEPA n.d.).

2.1 DIRECT GHG EMISSIONS OF HYDROPOWER

This section describes the *direct* GHG emissions of hydropower from operation of a hydropower facility. *Indirect* emissions occur during construction or decommissioning. Natural and manmade freshwater ecosystems emit greenhouse gases, largely due to the decomposition of biomass. Figure 1 shows the types of direct GHG emissions from hydropower reservoirs.

- **CO_2 emissions and carbon storage:** Carbon dioxide is produced by the decay of terrestrial biomass (trees, logs, leaves) when sufficient oxygen is available. CO_2 emissions are released at the water surface and during water turnover. Water turnover occurs naturally in cooler seasons as colder, denser water sinks to the bottom of reservoirs and the lower layers of water rise to the surface. CO_2 is highly soluble and diffuses across the air-water interface. In areas with similar climatic and ecological conditions, reservoirs and aerobic, natural freshwater bodies produce similar carbon dioxide emissions per unit area.

  Some carbon also accumulates in sediment in the bottom of reservoirs, lakes, and rivers. However, sediment only stores a fraction of the carbon input, and storage varies by climate, reservoir depth, and water level fluctuation. Also, sediment may be removed in maintenance and decommissioning and removal may result in emission of much of the stored carbon.

- **Methane emissions:** Anaerobic decomposition of organic matter produces methane. The organic material comes from the terrestrial biomass flooded during dam construction or deposited by runoff from watersheds and tributary water flows. Because methane is relatively insoluble in water, it is often released from water in bubbles (*ebullitive emissions*). The solubility of methane declines as water pressure decreases, causing the release of dissolved methane into the atmosphere. Methane emissions often occur through *degassing*, when deep water from the reservoir emerges from turbines and areas downstream of the impoundments as bubbles are

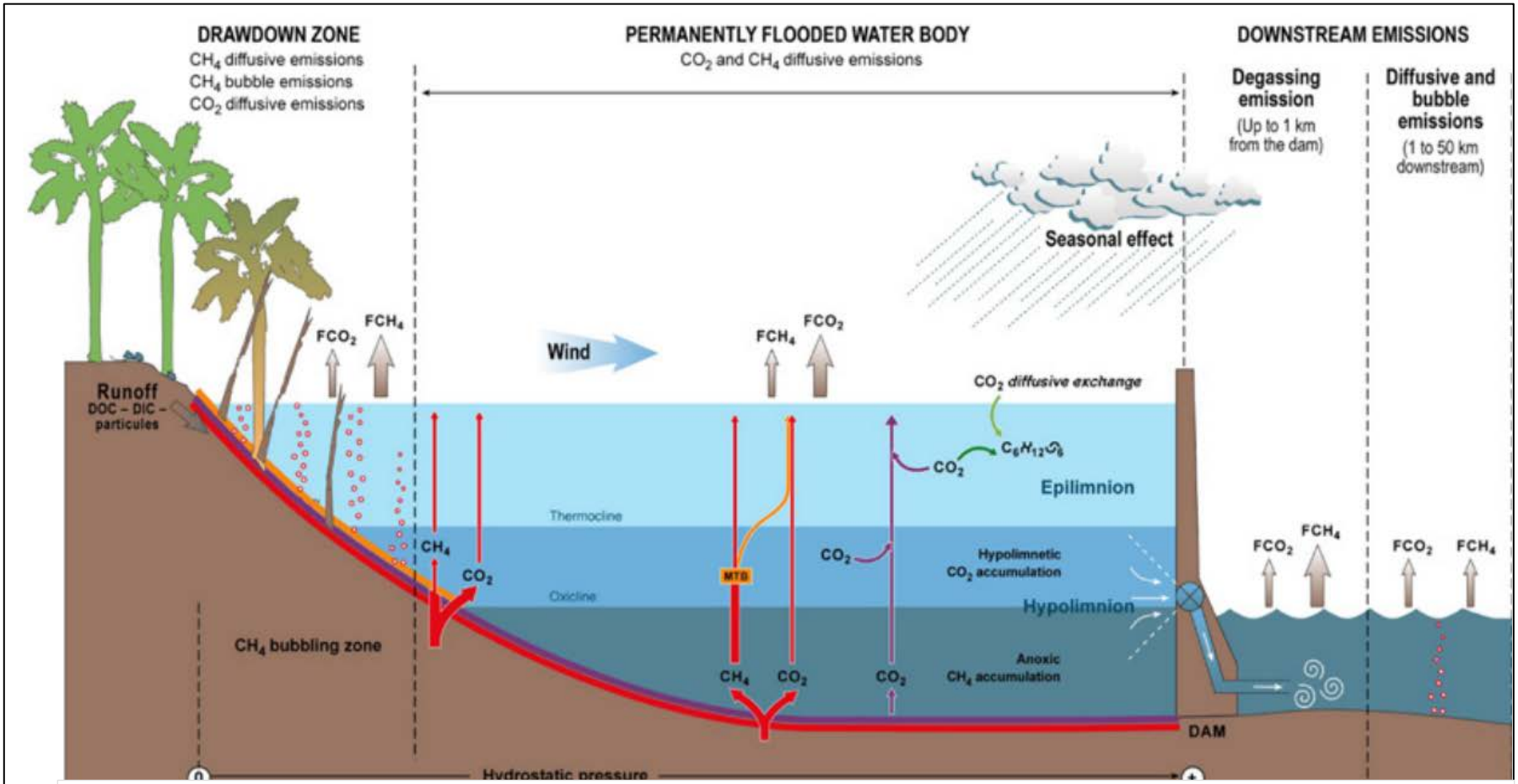
released from water at lower pressure. Most of the research on methane emissions from hydropower in the tropics has focused on the amount released from the reservoir surface. However, Kemenes, Forsberg, and Melack (2007) found that 55 percent of the annual methane emissions from the Balbina Dam in Brazil were downstream from the reservoir. This reservoir was nearly anoxic most of the year, leading to high methane concentrations.

- **Nitrous oxide** (N_2O) may also be an important source of GHG emissions from reservoirs with a large drawdown, especially in the tropics. However, there have been no global estimates of the N2O emissions (IPCC 2012).

Experts have criticized the lack of consistency and transparency in many existing studies of global GHG emissions from reservoirs and concluded that their comparability was limited. The most important flaw in the research to date may be that the estimates only considered gross GHG emissions and not the net emissions. The *net emissions* from hydropower also reflect the increase over the baseline emissions due to the land clearing and impoundment (Cullenward and Victor 2006; Tremblay *et al.* 2004; Barros *et al.* 2011; Deemer *et al.* 2016). Before establishment of a reservoir, the terrestrial vegetation on the site sequestered carbon. Afterwards, its continuing role in carbon uptake has been lost and the accumulated carbon in the cleared vegetation will eventually be released into the atmosphere.

Table 1 contains three estimates of global GHG emissions from hydropower and other reservoirs that ranged from 288 to 2,300 million metric tons of carbon dioxide equivalent (tCO_2e). These three studies were based on very different estimates of the emission rate per unit area, ranging from 823-2,365 tCO_2e per square kilometer (km^2). Surprisingly, the three estimates also reflected large differences in the global area of reservoirs from 310,000 to 1,500,000 square kilometers. Two of the studies included all types of reservoirs, while one only considered hydroelectric reservoirs. The comparability of these studies is limited due to differences in methods; reservoir types, sizes, and locations, and time periods. These three studies only accounted for gross emissions, rather than net emissions.

FIGURE 1. Main Processes for CO_2 and CH_4 Production in Tropical and Equatorial Reservoirs



MAIN PROCESSES FOR CH_4 and CO_2 PRODUCTION IN TROPICAL AND EQUATORIAL RESERVOIRS:

Methanogenic bacteria in anoxic sediments: $C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2$

Methanotrophic bacteria (MTB) in oxic sediments/water: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

Decomposition in oxic/anoxic sediments/water: $C_6H_{12}O_6 \rightarrow 6CO_2 + 6H_2O$

Photosynthesis: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6$

Source: Demarty and Bastien (2011).

TABLE 1. Estimates of Global GHG Emissions from Reservoirs

Scope and Source	Global GHG Emissions (Million tCO2e)	Area of Reservoirs (km^2)	Average Emission Rates Per Unit Area ($tCO2e/km^2$)
All types of reservoirs (Deemer *et al.* 2016)	733	310,000	2,365
All types of reservoirs (St. Louis *et al.* 2000)	2,300	1,500,000	1,533
Hydroelectric reservoirs only (Barros *et al.* 2011)	288	350,000	823

In the mid-2000s, researchers began to estimate GHG emissions from establishment of reservoirs as well as hydropower operations. Various studies have found that methane degassing from turbines and areas downstream of dams were major sources of GHG emissions in the tropics (Abril *et al.* 2005; Fearnside 2004 and 2005; Guerin *et al.* 2006; and Kemenes, Forsberg, and Melack 2007). The solubility of CH_4 declines as water pressure decreases. As deep water in a reservoir passes through a turbine or is released from the reservoir into a river, the less soluble CH_4 passes into the atmosphere. Deemer *et al.* (2016) estimated that CH_4 emissions constituted 80 to 90 percent of the GHG emissions from reservoirs. It is harder to accurately measure methane emissions from water than the carbon dioxide from water because methane from ebullition is more variable. Deemer *et al.* (2016) concluded that measurement difficulties contributed to the exclusion or incompleteness of CH_4 emission estimates from reservoirs in earlier research.

2.2 INDIRECT GHG EMISSIONS OF HYDROPOWER

Indirect GHG emissions from hydropower reservoirs are positively correlated with the total area flooded, volume of vegetation flooded, reservoir age below 10-15 years, location in the tropics, higher water temperature, shallow depths, eutrophication, and higher primary productivity. The GHG emissions tend to be higher with water intake from the deeper water layers. These effects are summarized in Table 2 and described in detail in sections 2.2.1 and 2.2.2.

TABLE 2. How Characteristics of Hydropower Dams Affect Indirect GHG Emissions

Characteristics	Effects on GHG Emissions Per Unit Area
Physical and Environmental Features	
Location in the tropics	Positive correlation
Volume of vegetation flooded in inundation	Positive correlation
Reservoir depth	Negative correlation: Shallow reservoirs generally have higher GHG emissions in the tropics because of faster decomposition of organic matter in warm climates
Age of reservoir	Initially higher emissions from reservoir inundation. Conflicting evidence on whether negative correlated beyond 10-15 years. Possible increases in emissions with sedimentation of older reservoirs.
Water temperature	Positive correlation
Inflows of organic matter from tributaries and watersheds	Positive corrrelation
High nutrient levels in water (eutrophication)	Increases algal blooms that may lead to short-term increases in carbon sequestration and long-term increases in CH_4 emissions
Sedimentation	Net effect unclear. Sedimentation increases carbon storage and also CH_4 emissions
Design and Operations	
Reservoir depth	Negative correlation
Operating characteristics	Positive correlation between degassing below turbines and downstream CH_4 emissions
Design and engineering characteristics	Variable: Design features that increase vertical mixing of turbine waters or aerating weirs can reduce CH4 emissions from degassing of outflows; turbine intakes that draw from deeper water increase CH4 emissions

Sources: Barros *et al.* (2011); Fearnside (2005); Kemenes *et al.* (2007); Galy-Lacaux (2007).

2.2.1 INDIRECT GHG EMISSIONS FROM PHYSICAL AND ENVIRONMENTAL FEATURES OF DAMS

Flooding of Terrestrial Vegetation. Construction of a new dam or reservoir generally involves flooding of terrestrial vegetation. In the tropics, many of these areas were previously covered with carbon-dense forests or wetlands. As a result of the flooding, the carbon stored in the biomass or soil undergoes bacterial decomposition that releases carbon dioxide and methane. If the terrestrial biomass is not cleared prior to inundation, the GHG emissions will be higher because of methane from decomposition of the vegetation in the water. The Tucuruí Dam in the Amazon inundated 20 million cubic meters (m^3) of timber (Nilsson and Beggren 2000).

However, there is generally a financial incentive to harvest timber before the land is inundated if the species are commercially valuable and the quality is good. In either case, loss of the vegetative cover eliminates the carbon uptake that would otherwise been stored by the vegetation in all future years. The net impact of a dam on GHG emissions depends on the dynamics of the ecosystem *before* reservoir

construction. If an area was a net GHG sink before the impoundment, the loss of future carbon sequestration due to the flooding should be counted in addition to the direct GHG emissions from the reservoir. Box 2 discusses GHG emissions from land clearing and flooding for the Balbina Dam in Brazil.

BOX 2. GHG Emissions from Land Clearing and Flooding for the Balbina Dam in Brazil

The Balbina Dam on the Uatumã River in Brazil is one of the largest reservoirs in South America with an area of 2,360 km^2 and a power generation capacity of 250 megawatts. Although baseline data were not collected, the Uatumã floodplain was likely to have been a net source of GHG emissions. Most of the region flooded in construction of the dam was upland tropical broadleaf forest. Accounting for the GHG fluxes in both the floodplain and upland forest, the area flooded in developing the Balbina Dam was likely to have been a net GHG sink prior to the impoundment (Kemenes, Forsberg, and Melack 2011).

Latitude and location. Reservoirs generally have higher GHG emissions in the tropics than in temperate areas. A meta-analysis of GHG emissions from 85 hydropower reservoirs found that the higher water temperatures and larger volume of flooded biomass in the tropics were strongly correlated with higher GHG emissions (Barros *et al.* 2011). In addition, reservoirs in the tropics tend to have greater thermal stratification of water. As a result, the bottom waters of reservoirs are typically anoxic (oxygen depleted), which increases methane production (Mendonça *et al.* 2012; Barros *et al.* 2011). Barros *et al.* (2011) found that dams in the Amazon had higher average gross GHG emissions per square meter than dams in other tropical areas.

Amount and type of organic matter. Net emissions from a reservoir vary with the amount of organic material flooded during construction. Different types of organic matter decompose at different rates. For example, a submerged tree bole decomposes relatively slowly while leaves and plant litter undergo rapid decomposition (St. Louis *et al.* 2000).

Reservoir age. Two meta-analyses found that newer reservoirs had higher GHG emissions than older reservoirs. Younger reservoirs may contain more decomposable vegetation and soil organic matter. In addition, aerobic bacteria respiration rates may be relatively high in the early years after the land is inundated (Mendonça *et al.* 2012; Barros *et al.* 2011). However, another meta-analysis concluded that the relationship between a younger reservoir age and GHG emissions was weaker than previously thought (Deemer *et al.* 2016). Other factors, such as higher primary production and eutrophication from greater sediment and runoff may increase the GHG emissions from older reservoirs.

Primary production. *Primary production* refers to the synthesis of organic compounds by living organisms, mainly through photosynthesis. High chlorophyll levels in water indicate high *net primary production,* and are positively correlated with the carbon content and negatively correlated with dissolved oxygen. Deemer *et al.* (2016) found that chlorophyll concentrations were the best predictor of total CH_4 emissions diffusing from the water surface or bubbling up through the water. High carbon and low dissolved oxygen levels both favor production of CH_4 over carbon dioxide. Aquatic bacteria generally convert organic matter derived from algae into methane at a faster rate than organic matter from terrestrial carbon.

Eutrophic systems. Sedimentation and runoff increase nutrients in reservoirs and other downstream areas in the watershed over time. High nutrient levels accelerate growth of aquatic plants, especially algae and floating macrophytes such as water lilies and water hyacinths. Although algae growth increases atmospheric carbon uptake for a while, high nutrient concentrations in the water lead to cycles of algal blooms and death (*eutrophication*). As the dead algae decompose, dissolved oxygen levels in the water decrease and it may become anaerobic, which leads to higher methane emissions (Fearnside 2005).

Eutrophic reservoirs have a high concentration of nutrients and plant growth and often develop low dissolved oxygen levels after the death and decomposition of algal blooms. Meta-analyses have differed on whether eutrophic reservoirs have higher methane emissions. High nutrient levels can increase phytoplankton productivity and organic carbon storage (Mendonça *et al.* 2012). Barros *et al.* (2011) found that eutrophic reservoirs were generally carbon sinks, regardless of their age or latitude. However, Deemer *et al.* (2016) concluded that CH_4 emissions were significantly higher in eutrophic reservoirs because of lower dissolved oxygen levels in the bottom waters and high primary production and CH_4 emissions from the surface waters.

2.2.2 INDIRECT GHG EMISSIONS FROM RESERVOIR DESIGN AND OPERATIONS

Differences in the design and operation of hydropower reservoirs affect the GHG emissions:

Dam Design

- **Upstream versus downstream location.** Dams upstream of major nutrient deposition sources tend to have lower methane emissions than downstream dams. Dam designs that address local terrain and flow dynamics to reduce nutrient deposition and eutrophication can reduce CH_4 emissions (Deemer *et al.* 2016).
- **Reservoir depth and volume**. In general, methane emission rates decrease as the average reservoir depth increases. Bacteria oxidize methane in the water column and release it as carbon dioxide. Bacteria can oxidize more of the methane in deep reservoirs because of the greater distance to the water surface (Barros *et al.* 2011).
- **Drawdown.** Methane emissions tend to be higher where there is a large *drawdown* (difference between the height of the reservoir at maximum and minimum water withdrawal rates). Drawdown rates for hydropower and other purposes are generally higher in drought years. The Tres Marias Dam in Minas Gerais, Brazil has a relatively high, nine-meter drawdown. Thirty-six years after construction, the Tres Marias dam's the surface GHG emissions were higher than those of fossil fuel power plants with a similar capacity (Fearnside 2005).

Dam Operations

- **Degassing of Turbines.** As water passes through turbines and out of a reservoir, the water pressure decreases and dissolved CH_4 gas is released. This degassing can be a major source of methane emissions, particularly if the water is from the bottom of the reservoir (Fearnside 2005, 2012; Guerin *et al.* 2006; Galy-Lacaux *et al.* 2007). Barros *et al.* (2011) estimated that methane emissions from degassing of turbines accounted for less than half of the total GHG emissions from hydropower. However, this estimate was based on a low value of 25 for the 100-year GWP of methane. The IPCC's more recent estimate is that methane has a GWP of 34.

  Other studies have found higher methane emissions from degassing at the turbine outflow. Fearnside (2012) reported that the Tucuruí Dam in Brazil had methane emissions from degassing at the turbine amounting to 90 percent of the dam's total GHG emissions. By contrast, the Petit Saut Dam in French Guiana had lower downstream emissions of methane because its design increased mixing of turbine waters, reducing emissions from degassing at the turbine outflow. In general, degassing emissions are proportional to the stream flows. Deemer *et al.* (2016) found that methane dominated total GHG emissions from reservoirs and concluded that methane emissions from degassing of turbines and downstream bubbles were underestimated in previous studies.

The amount and types of GHG emissions from hydropower vary with characteristics of the dam and local biophysical characteristics. The relationships among these variables and GHG emissions are complex, making GHG emissions difficult to predict (Kumar and Sharma 2012).

Dam Decommissioning:

- GHG emissions from decommissioning of reservoirs have generally not been considered. Relatively few dams have been removed and most of these were relatively small and located in the temperate United States (IPCC 2012).

2.3 COMPARISON OF GHG EMISSIONS OF HYDROPOWER WITH OTHER SOURCES OF ELECTRICITY

This section compares the GHG emissions from hydropower to other sources of electricity. This comparison is necessarily limited because most of the literature does not include the full life cycle GHG emissions from hydropower or its alternatives. It often does not account for the GHG emissions associated with construction, maintenance, and decommissioning of hydropower, fossil fuel, nuclear, or renewable energy power plants. For example, the GHG emissions from production of concrete and steel for dams and power plants, extraction and transport of fossil or nuclear fuels, and disposal of waste products from fossil or nuclear fuels are often excluded.

2.3.1 COMPARISON OF DIRECT GHG EMISSIONS

Over the past two decades, there has been considerable scientific debate on the direct GHG emissions from development and operation of new, large hydropower facilities in the tropics. All other things equal, the GHG emissions from a hydropower reservoir tend to be higher in the tropics because of the higher rate of primary production. Multiple researchers have concluded that hydropower was more carbon intensive than thermal power plants, based on studies of the Tucuruí, Balbina, and Curuá-Una Dams in Brazil and the Petit Saut Dam in French Guiana (Giles 2006; Fearnside 2004; Fearnside 2005; Kemenes *et al.* 2007; Guerin *et al.* 2006; St. Louis *et al.* 2000). However, Rosa *et al.* (2004) reported examples of hydropower facilities that were less carbon-intensive than natural gas and coal-fired power plants. Box 3 discusses the Mekong River Commission's questionable estimates of the direct GHG emissions from hydropower in the Lower Mekong Basin.

BOX 3. Hydropower and GHG Emissions in the Lower Mekong Basin

The Mekong River extends for 4,350 kilometers in Southeast Asia (Beilfuss and Triet 2014). The Lower Mekong Basin (LMB) consists of the mainstream of the Lower Mekong River and its tributaries. The installed capacity of hydropower dams in the Lower Mekong Basin was approximately 13,000 MW. An additional 29,000 MW of hydropower have been proposed, for a total capacity of nearly 42,000 MW in more than 170 hydropower dams. Much of the proposed new hydropower capacity would be located in Laos and serve export markets for electricity (Beilfuss and Triet 2014).

The Mekong River Commission (MRC) is an intergovernmental organization that works with the governments of Cambodia, Laos, Thailand, and Vietnam on shared water resource management. The MRC estimated that substituting new hydropower dams in the Lower Mekong Basin (LMB) could avoid 42-94 million tCO_2e in annual GHG emissions from fossil-fuel fired power plants by 2030. The large range reflected different scenarios of electricity demand growth and hydropower development. The MRC estimated that the hydropower dams would generate 13 million tCO_2e/year, reducing emissions by 29-81 million tCO_2/year (Beilfuss and Triet 2014).

Since the MRC is a strong proponent of hydropower development in the region, its estimates should be interpreted with caution. The MRC did not consider the alternatives of utility-scale solar and wind power, which have greatly declined in cost since it formulated its hydropower plans. It is also unclear whether it adequately included GHG emissions from clearing and flooding of the land. Other studies have concluded that some specific, proposed dams in the LMB may have GHG emission levels similar to a coal-fired power plant (Lee and Yan 2013). The MRC estimates of GHG reductions from large hydropower need further review.

Some of the discrepancies in the findings on the direct GHG emissions may be due to the small sample of large hydropower facilities in the tropics studied. The GHG emissions of hydropower can vary greatly due to site- and project-specific conditions and cannot be easily extrapolated to different facilities in other locations. The correct denominator for comparing GHG emissions per unit of electricity is average annual generation, rather than total plant capacity. *Average annual generation* accounts for differences in capacity factors across power sources.

Dos Santos *et al.* (2006) found that average direct GHG emission rate of nine hydropower reservoirs in Brazil was one-fifth that of typical coal- and oil-fired power plants. However, this study only compared gross direct emissions from hydropower systems. It did not account for the GHG emissions from construction of the impoundment. Natural gas combined cycle plants are generally the most carbon-efficient fossil fuel source of electricity because they use a steam turbine as well as a gas turbine. Waste heat from the gas turbine runs the steam turbine to generate additional electricity. Dos Santos *et al.* (2006) found that a natural gas combined cycle power plant had three times the average GHG emissions rate of hydropower. However, a few hydropower dams had a slightly higher GHG emissions rate than

the natural gas combined cycle power plant. The GHG emissions for natural gas power plants should include the fugitive emissions from transmission and distribution of natural gas. Dos Santos *et al*. (2006) reported that fugitive emissions of natural gas in Brazil were 4.7 percent.

2.3.2 COMPARISON OF LIFE CYCLE GHG EMISSIONS

Life cycle assessments (LCAs) consider the full range of GHG emissions from commissioning, building, operating, and decommissioning a power plant, including the entire fuel cycle. A life cycle assessment for hydropower should include the emissions from developing and operating a dam as well as manufacturing and transporting the construction materials. However, none of the studies estimated GHG emissions from the production of concrete or steel for dam construction. Fossil fuel production and transport generates substantial GHG emissions that should be included in calculating the relative GHG emissions from thermal power plants. Although natural gas is a cleaner fuel than coal, GHG emissions in natural gas extraction and processing, venting wells, operation of pipelines and compressor stations, and leakages in transmission and distribution systems should also be counted. Dos Santos *et al*. (2006) reported that the *losses* in transmission and distribution of natural gas were 4.7 percent in Brazil. Littlefield *et al*. (2016) reported that these *fugitive losses* of natural gas have been underestimated as a source of methane emissions.

Power density refers to the power generation capacity of a hydroelectric facility per unit area flooded. Hydropower systems with a relatively high power density generally have low life cycle GHG emission rates (Hertwich 2013). Most hydropower dams have power densities around 1.0 watt per square meter ($W/m^{2)}$ (Fearnside 2005). If the power density is below 0.1 W/m^2, the life cycle GHG emissions from hydropower can be higher than those from fossil fuel power plants (Fearnside 2004; Demarty and Bastien 2011). The Balbina Dam in Brazil had a power density of 0.14 W/m^2. It was only operating at 50 percent of its rated capacity and released 2.9 tCO2e per MWh of electricity generated, much higher than the 1.1 tCO2e per MWh for a coal-fired power plant of similar capacity (Kemenes et al. 2011).

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reviewed existing studies and noted that the GHG emissions from hydropower were highly site-specific. Figure 2 below shows the estimated life cycle GHG emissions for hydropower and alternative sources of electricity. Most hydropower systems had life cycle GHG emissions between 4 and 14 kg CO_2e/MWh. Run-of-river systems had lower GHG emission rates than dam-based systems. The worst-performing hydropower dams are located in the tropics with relatively large impoundment surface areas and relatively low electricity production. These dams had GHG emissions of up to 150 kg CO2e/MWh, although estimates of the maximum life cycle emissions for hydropower exceeded even coal-fired power plants at up to 2,200 kg CO2e/MWh. However, estimated median life cycle emissions from world average coal-fired power plants were 1,050 kg CO2e/MWh, with slightly higher maximum (IPCC 2015).

Some of the variation across IPCC-reviewed studies reflected differences in the carbon stock of the flooded area, expected lifetime of the system, turbine efficiency, residence time of water and the study area boundaries. Higher estimates often included initial and ongoing effects of land use changes associated with reservoir inundation (e.g., methane from soil and vegetation decomposition) and sometimes included decommissioning. Only two reviewed studies included the impact of releasing accumulated sediment in decommissioning. IPCC called for additional life cycle studies covering a broader range of climate zones, technology types, and dam sizes (IPCC 2012).

Hertwich *et al*. (2015) conducted a literature review and measured methane emissions from hydropower. They estimated a global average of 85 kg CO_2/MWh plus 3 kg CH_4/MWh for hydropower emissions, with an uncertainty factor of two. The total GHG emissions were 193 kg CO_2e/MWh based on a global warming potential of 36 for methane. Hertwich *et al*. (2015) found that hydropower generally had higher life cycle GHG emissions that were higher than wind and solar power, but lower

than natural gas- or coal-fired electricity. However, they reported that there were fewer LCA studies for hydropower than other power generation alternatives despite the fact that GHG emissions from hydropower are more project- and site-specific. They also noted that hydropower requires more land per unit of electricity generation than wind, solar, coal, and natural gas power.

Turconi, Boldrin, and Astrup (2013) reviewed 167 life cycle assessments of various electricity generation technologies, including five for hydropower dams and seven for run-of-river systems. They found that hydropower typically had life cycle GHG emissions similar to those of wind, photovoltaics, and nuclear power, but far less than power plants fueled with coal, oil, or natural gas (Table 3). However, there was a lot of variation in the reported life cycle GHG emissions for hydropower and other fuels.

TABLE 3. Life Cycle GHG Emissions By Type of Powerplant

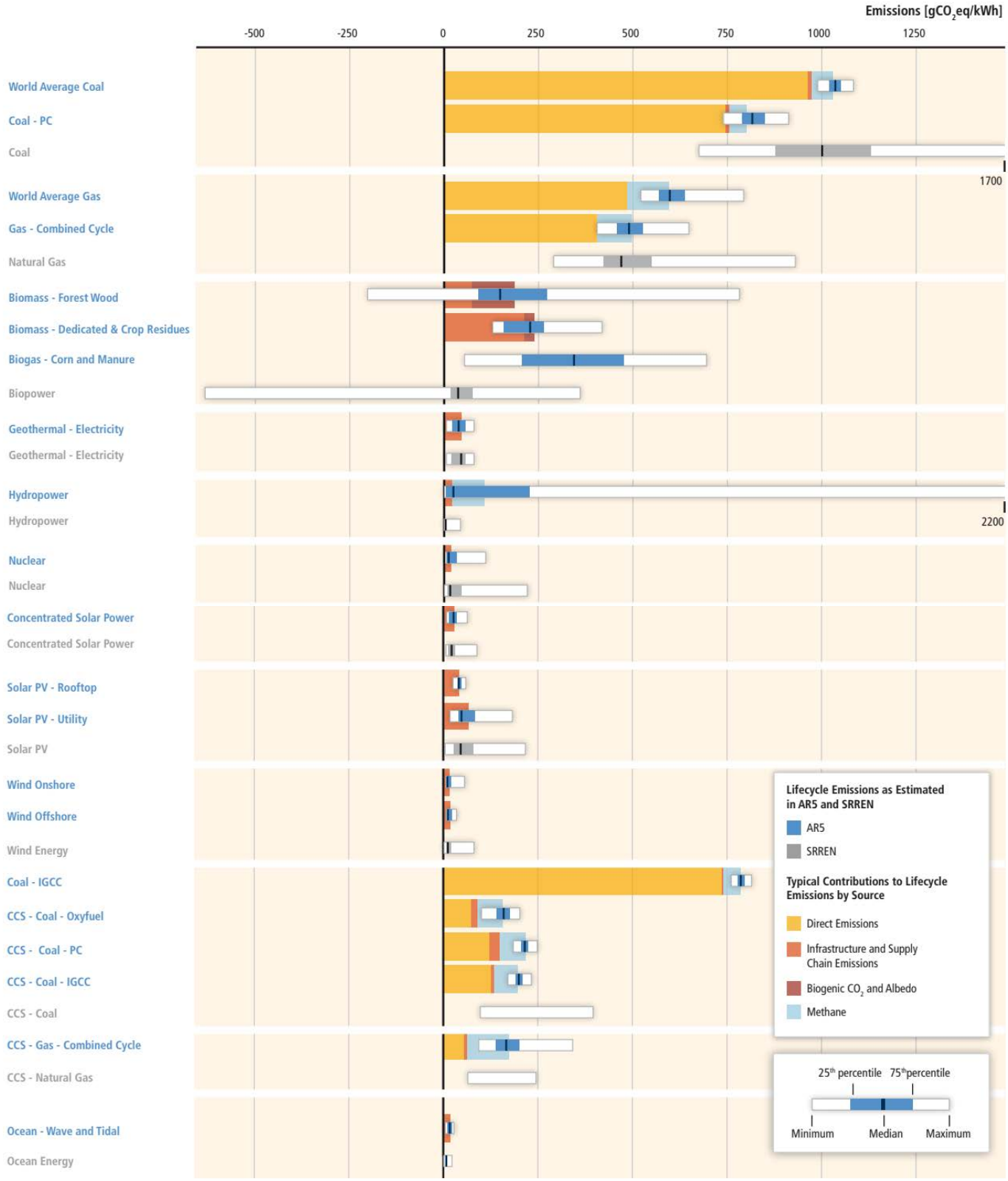
Type of Powerplant	Life Cycle GHG Emissions (kg CO_2e/MWh)
Hydropower reservoir dams	11-20
Hydropower run-of-river systems	2-5
Hard coal thermal plant	660-1,050
Lignite thermal plant	800-1,300
Natural gas thermal plant	380-1,000
Petroleum thermal plant	530-900
Nuclear	3-35
Photovoltaics	13-130
Wind power	3-28

Adapted from Turcorni, Boldrin, and Astrup (2013)

The life cycle GHG emissions from hydropower range widely. The authors attributed much of the variation to differences in methane production, which vary with the climate, reservoir size, water depth, type and amount of flooded vegetation and soil type. For example, GHG emissions from hydropower ranged from 0.35 kg CO_2e/MWh in alpine regions to 30 kg CO_2e/MWh in Finland and 340 kg CO_2e/MWh in Brazil (Turconi, Boldrin, and Astrup 2013).

The available studies showed that hydropower reservoir dams typically have far lower life cycle GHG emissions than coal, petroleum, or natural gas thermal power plants and similar life cycle GHG emissions to nuclear, photovoltaics, and wind power systems. The life cycle GHG emissions from photovoltaics and wind power varied with the source of the electricity used in manufacturing the panels and the climate where they were installed. However, there is much uncertainty about the direct and indirect GHG emissions from hydropower. Furthermore, some notable hydropower systems had GHG emissions as high or higher than thermal power plants. Careful decisions on the location and design of dams are critical for reducing their life cycle GHG emissions of hydropower.

FIGURE 2. Life Cycle GHG Emissions of Energy Technologies (Grams of CO_2e/KWh)



Source: IPCC (2015). *Note*: Blue labels represent estimates from *Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the IPCC Fifth Assessment Report.* (IPCC 2015). Gray labels represent estimates from *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* (2012). Note that g/KWh is an identical measure to kg/MWh used elsewhere in this report.

2.4 KEY FINDINGS AND RECOMMENDED PRACTICES FOR REDUCING THE GHG EMISSIONS OF HYDROPOWER

Key Findings

A. The most important factor in the GHG emission rate for hydropower is power density, which depends on the reservoir surface area and amount of electricity generated. Although hydropower generally has life cycle GHG emission rates similar to other renewable power technologies, some large hydropower facilities with low power densities had high emission rates.

B. Location is often the second most important factor in GHG emission rates for hydropower. Hydropower dams have higher GHG emission rates in the tropics than in temperate or boreal areas.

C. Life cycle GHG emissions for hydropower vary by type of system. Hydropower dams have higher life cycle emissions than run-of-river systems. Pumped storage can have a high GHG emissions rate per unit of usable power due to the electricity used in pumping water uphill so that electricity could be regenerated later when needed.

D. The net GHG emissions from hydropower are substantially greater than the gross emissions. The net emissions include the initial and continuing impacts of clearing vegetation and inundation of the land.

E. None of the reviewed studies disaggregated the GHG emissions over the life cycle of the hydropower facilities. Disaggregated estimates of GHG emissions at each stage of the life cycle are needed to improve management of hydropower impacts.

Recommended Practices

A. Analyzing Impacts on GHG Emissions:

- Estimate the net GHG emissions from hydropower development, including the emissions due to the reservoir flooding and post-impoundment operations.
- Assess facilities on a location- and case-specific basis.
- Compare the life cycle emissions for hydropower and other sources of electricity, including those from downstream impacts and the fuel production cycle.

B. Reducing GHG Emissions of Hydropower

- Minimize the area flooded and clear biomass from the area prior to flooding.
- Maximize the power density of a new reservoir, measured in W/m^2 of reservoir area.
- Design turbine intakes to draw water from the upper levels of the water column above the anoxic, methane-rich, lower water layers, and allow CH_4 oxidation as it rises through the water column. Aerate water after it passes through the turbine to release much of the methane so that it can be captured and flared to release CO_2, or fed into a generator to produce additional energy.
- Locate reservoirs upstream of major nutrient sources and adopt other strategies to reduce nutrient loadings.
- Place a higher priority on run-of-river hydropower over reservoir-based systems.

3. OTHER ENVIRONMENTAL AND SOCIAL IMPACTS OF HYDROPOWER

Table 4 summarizes some other common types of environmental impacts of hydropower dams and provides examples from specific locations. Dams for hydropower or other purposes typically obstruct approximately two-thirds of the volume of water in a river from flowing to the oceans (Nilsson and Berggren 2000). Dams can reduce fish and rice production by altering water flows and reducing river sediment and nutrient loads downstream. These changes can degrade aquatic habitat and disrupt the food web affecting fish survival, reproduction and migration (Wild and Loucks 2014). Deposition of river sediment on land through regular, small flooding can reduce land subsidence risk and increase the fertility of cropland.

The alteration of river flows has substantial impacts on freshwater ecosystems through disruption of fish migration for feeding and spawning; changes in water quality and chemistry, increases in sediment deposition in the watershed, and destruction of habitat from inundation and reduced connectivity. Finer and Jenkins (2012) reviewed environmental impact assessments for 151 planned dams in the Andean Amazon and found that 47 percent were expected to have large environmental impacts from blocking downstream sediment flows and fish migration paths. Box 4 discusses the impacts of proposed hydropower dams in the Lower Mekong Basin on fish and rice production.

TABLE 4. Other Environmental Impacts of Hydropower

Type of Impact	Description	Examples
Hydrology/flow regimes	Dams alter total downstream water flows and reduce flood peaks and overbank flooding.	Hadejia River, Nigeria: Annual downstream flows decreased by one-third after construction of the Challawa Gorge and Tiga dams (McCartney 2009).
Thermal regimes	Dams increase heat storage and seasonal stratification of water. The coldest water is usually in the deepest layers of a reservoir.	Surna River, Norway: Water temperatures decreased by 6-8°C downstream of the hydropower dam, reducing the growth of salmon and trout (McCartney 2009).
Water chemistry	As organic matter in reservoirs decomposes, nutrient levels and biochemical oxygen demand increase, reducing the dissolved oxygen content of the water. Evaporation of water from a reservoir can increase salinity levels in the outflows downstream.	Niger River, Nigeria: The density of phytoplankton doubled downstream of dams due to high nutrient levels (McCartney 2009). Elefantes River, Mozambique: Salinity increased downstream of the Massingir Dam (McCartney 2009).
Sedimentation	Reservoirs reduce the velocity of river flows, causing sediment to accumulate behind dams. High sedimentation rates can reduce the effective life of the dam by decreasing storage capacity, efficiency of water use, and abrading turbines (Annandale *et al* 2016). Reservoirs may reduce downstream sediment loads, decreasing nutrient levels for aquatic ecosystems, increasing river bank erosion, and degrading coastal deltas and beaches.	Snake River, Idaho, USA: The sandy beach area decreased 75 percent following trapping of five million tons of sediment per year in upstream reservoirs (McCartney 2009). India: Eleven large reservoirs are filling with sediment much faster than expected, ranging from 130 per cent higher at at Bhakra to 1,650 percent at Nizamsagar (McCulley 1996).
Primary production	Reduced plant growth and reproduction from changes in water flows, chemistry, and temperatures downstream of a dam can adversely affect the food web.	Aswan High Dam, Egypt: Fish production collapsed after deliveries of nitrogen an phosporus to the lower river and coastal Mediterranean waters were substantially reduced (Nixon 2003).
Fisheries	Fish abundance and biodiversity can be reduced by and changes in water flows, chemistry, and temperatures that disrupt habitat, food supplies, migration, and reproduction.	Petit Saut Dam, French Guiana: The number of major fish species downstream in the Sinnamary River declined from 54 to 37 after dam construction (McCartney 2009).
Plants and animals	Flooding can reduce abundance and biodiversity of plant and animal species.	Xinjiang Dam, China: River dolphin population fell to zero after dam construction (McCartney 2009).

BOX 4. Impacts of Hydropower on Fish Production in the Lower Mekong Basin

The Mekong River is the world's largest inland fishery, providing an annual catch with a gross value of $5.6-$9.4 billion. Approximately 60 million people depend on fish and shellfish from the Lower Mekong Basin as their primary protein source (Cronin and Weatherby 2015). The Mekong River Delta supplies most of Vietnam's seafood exports as well as half of the country's rice production and nearly 90 percent of its rice exports.

The Mekong River Commission (2011) estimated that proposed dams in the Lower Mekong Basin could have negative effects on the livelihoods of 1.6-3.5 million people in Cambodia, Laos, Thailand, and Vietnam through reduced fish catches. Since the Mekong River Commission is a strong proponent of hydropower development, additional research may be needed on the magnitude of the fish catch reductions and resulting economic and social impacts. Smaller fish catches are likely to raise fish prices and may decrease protein consumption or increase pressure on land and water resources to substitute terrestrial protein sources (International Rivers 2009, Orr *et al*. 2012).

Approximately 70 percent of commercial fish species in the Lower Mekong Basin migrate long distances (International Rivers 2009). Dugan *et al*. (2010) noted that existing technology for mitigating the impacts of dams on fisheries (such as fish ladders, fishways, locks, and lifts) cannot sustain the volume of fish migration in the basin, which is much larger than in European and North American rivers. The authors recommended additional investment in improving fish passage technologies and alternative livelihood strategies to manage the economic impacts from the loss of fisheries.

Wild and Loucks (2014) estimated that 40 to 80 percent of the Mekong River's annual suspended sediment load could be trapped in reservoirs if proposed dams are developed. Development of dams could also adversely affect the Tonle Sap in Cambodia. This seasonally flooded lake with an attached river is important for inland fishing as well as flood recession rice production in the dry season.

Concern over domestic and transboundary environmental impacts from the partly constructed Xayaburi hydroelectric facility in the Lower Mekong Basin in Laos led to design changes to improve fish passage and sediment transfer. For example, four of the eleven gates in the spillway were redesigned as low-level outlets that flush sediments downstream, increasing the dam's capacity to handle sediment loads from heavy rains (Cronin and Weatherby 2015).

Multiple dams in a river basin can have cumulative effects on the hydrology and natural systems. Timpe and Kaplan (2017) found that rivers in the Brazilian Amazon with multiple dams had a higher frequency and duration of high and low pulses of water than those with a single dam. However, they found no significant difference in the total water flows, but these findings may reflect differences in the sizes of those dams. Multiple dams on a river system can reduce floodplain and aquatic productivity (Forsberg *et al*. 2017). The authors modeled the effects of six large dams planned in the Andean region of the Upper Amazon and found aquatic productivity reductions down to the lowland floodplains. The model assumed that fish yields declined linearly with the reduction in annual peak flows. Winemiller *et al*. (2016) recommended updating environmental assessment protocols to address cumulative impacts on hydrology and ecosystem services and validate mitigation measures.

Hydropower development generally also requires the construction of temporary or permanent roads to access hydropower resources in remote areas. This report does not address the impacts due to road construction, but development or expansion of rural roads can also have environmental impacts in the tropics, including increased deforestation and associated GHG emissions, impacts to wildlife, and increased air pollution emissions (Smith, Hyman, and Cooley 2018).

3.1 SOCIAL AND CULTURAL IMPACTS OF HYDROPOWER

3.1.1 DISPLACEMENT AND RESETTLEMENT

The establishment of large-scale hydropower dams can result in displacement or resettlement of large numbers of people. Displacement and resettlement can have substantial negative social and cultural impacts on

- Household size and structure,
- Employment and incomes,
- Access to land and water resources,
- Social network and community functioning,
- Public health, and
- Psychological well-being (Tilt *et al.* 2009).

The effects can be particularly serious on indigenous groups and other marginalized populations. The social impacts of hydropower facilities are often difficult to measure due to inadequate baseline and control data. Adequate cash or in-kind compensation is rarely available to offset the losses incurred.

The Aswan High Dam in Egypt created an enormous reservoir, Lake Nasser, with a surface area of 5,250 km^2. Financing and construction started in 1960. The first dam was completed and filling of the reservoir began in 1964. The project was completed in 1970. Approximately 100,000 people were relocated for this dam, which has a hydropower capacity of 2,100 MW (Wikipedia 2018a). International Rivers (2009) reported that completion of the partly constructed Xayaburi Dam and 11 proposed, large dams on the mainstream of the Mekong River in Laos would require resettlement of 88,000 people.

The 22,500 MW Three Gorges Dam in China resulted in displacement on a far larger scale due to the high population density in the affected areas. This dam, the world's largest in hydropower capacity, was completed in 2015. It displaced more than one million people over a 20-year period of development and construction (Wilmsen 2016). Initially, the Government of China resettled affected farmers on "reclaimable" land, with steep slopes and high rates of erosion and land degradation (Wilmsen 2016).

In 2002, a survey of found that the average incomes of affected households resettled for the Three Gorges Dam declined 10-23 percent in the first five years after resettlement (Wilmsen, Webber, and Yuefang 2011). In 2003, rural populations resettled in Zigui had incomes 80 percent below those of non-resettled populations nearby. A subsequent study found that the average income of resettled people in Zigui and Badong increased 400 percent between 2003 and 2011, a larger percentage increase than for non-resettled people nearby. However, the average income was still lower for the resettled people than non-resettled people. By 2011, incomes for the resettled people were only 20 percent below those of the control group (Wilmsen 2016).

Population displacement can also reduce social capital. Tilt and Gerkey (2016) surveyed 729 households in China and found that displaced households provided four fewer person-days of agricultural labor to their neighbors and received two fewer person-days of labor than non-resettled households. Displaced households also borrowed and loaned less money to their neighbors. The sample included people displaced by four dams in China, the oldest of which was completed in 1996. These impacts persisted for 20 years.

Nguyen *et al.* (2017) found that resettlement for the Binh Dien Dam in central Vietnam reduced social capital and incomes of the affected populations. Farmers in one village reported that the land area available a for upland rice cultivation decreased from 78 hectares to 10 hectares as a result of the resettlement. There was also a 90 percent decrease in the total fish catch and a 62 percent and 88

percent decline in the number of households collecting of honey and rattan from the forest, respectively.

There is little literature on the gender impacts from resettlement for hydropower. Mathur (2007) reported that 62 percent of the women displaced by the Upper Krishna Irrigation Project in India thought they had less disposable income after they were resettled. However, some women reported that resettlement decreased the distance they had to walk to collect water. Lahiri-Dutt and Ahmad (2012) argued that existing social impact assessment frameworks have not adequately addressed differential impacts on women and girls. The World Health Organization (2014) noted that resettlement for hydropower projects may have disproportionate impacts on women, based on experience with resettlement due to natural disasters and conflicts.

Furthermore, concerns have often been expressed about bias in these assessments since most are funded by proponents of the proposed investments and prepared by consultants who have their own special interests in continuing to be hired for work. There have been also criticisms about inconsistent application of the social and environmental impact assessment tools. McDonald-Wilmsen and Webber (2010) argued that large financial institutions have encouraged developing nations to develop their own resettlement policies, but have provided little guidance on avoiding the negative impacts of resettlement. As a result, hydropower developers typically try to minimize the cost of compensating for displacement, rather than avoiding displacement.

Concerns about social impacts and the breadth of local participation in the planning and approval for large hydropower dams can block dam construction and operations or cause many years of delay. The Barro Blanco Dam in Panama is a noteworthy example (Box 5).

BOX 5. Delays in Completion of the Barro Blanco Dam in Panama

The Government of Panama awarded a tender to Generadora del Istmo S.A. (GENISA) in 2006 to prepare studies and obtain approvals for the Barro Blanco Dam on the Tabasara River. The Government of Panama approved the project in 2008. In 2009, GENISA requested a modification of its development permit to increase the capacity by 52 percent and this was approved in 2010. Later that year, nongovernmental organization (NGO) protests of human rights abuses convinced the European Investment Bank to conduct an investigation that later resulted in withdrawal of its financing. The German Investment Corporation (DEG), Netherlands Development Finance Company (FMO), and Central American Bank for Economic Integration subsequently provided financing for construction. In 2011, the Clean Development Mechanism (CDM) under the United Nations Framework Convention on Climate Change (UNFCCC) approved issuance of carbon offset credits for this dam. In 2012, local people occupied the site and halted construction.

The developer claimed that no displacement of existing infrastructure or resettlement would occur (GENISA 2012). The indigenous community contended that the local consultations focused on non-indigenous people and people interested in selling their land. The indigenous community claimed that the dam would harm the livelihoods of 5,000 household by affecting access to the river for potable water, agriculture, and fishing; cutting primary forest; and increasing flood risks. In 2013, three CDM reports that concluded that there would be no significant impacts on global biodiversity, but the dam would have important impacts on indigenous populations and that they had not been properly consulted. A joint, external review for the two European development banks concluded that the banks' standards for consultations with indigenous communities had not been met (FMO-DEG 2015).

A new President of Panama suspended construction of the dam in February 2015 on the grounds of a flawed environmental and social impact assessment. Protests against this dam in June 2015 shut down the Inter-American Highway for two days. In August 2015, the President of Panama and an indigenous leader agreed that construction of the civil works could resume, but filling of the reservoir and installation of electromechanical works would be prohibited until a final agreement was reached with the indigenous communities. In September 2015, Panama's environmental agency fined GENISA $775,200 for failure to comply with agreed resettlement and compensation measures.

In early 2016, a report concluded that the design was technically safe. Filling of the dam began in May of 2016, causing the inundation of houses, farm land and access roads in multiple communities. This led to protests and roadblocks. The government and the community's leader reached an agreement on the dam's completion in August of 2016 that included removal of GENISA as the operator. This agreement was voted down by the indigenous community's general congress in September 2016 and the community leader who signed the agreement was ousted.

In November 2016, Panama's Ministry of the Environment, MiAmbiente, asked the UNFCCC to withdraw CDM registration for carbon credit eligibility because the application had been based on an outdated environmental impact assessment for a smaller 19 MW system. MiAbiente asked GENISA to submit a revised CDM application for a 28 MW system. However, the UNFCCC did not withdraw the original CDM registration. The General Administrator of Panama's National Authority for Public Services declared that the Ngäbe-Bugle General Congress never presented a formal rejection document to the government. Panama's Supreme Court ruled against the last two legal actions on the dam by the indigenous communities.

GENISA completed testing of the facility and received approval from the national energy regulator to begin operations in March of 2017. Ngäbe communities along the Tabasará River reported that filling of the dam damaged their banana crops and wood resources and flooded some houses. The Government of Panama has not moved forward on forced resettlement of the communities (Giraldo 2017).

3.1.2 CULTURAL AND ARCHEOLOGICAL IMPACTS

Large hydropower can also have substantial cultural and archeological impacts. In some cases, loss of some treasures from the world's heritages can be avoided at high cost by relocating within or outside the country. This was done for the Aswan High Dam in Egypt.

Twenty monuments or architectural complexes from Egypt and four from Sudan threatened by flooding of the reservoir were saved. The United Nations Educational, Scientific and Cultural Organization (UNESCO) funded disassembly, relocation, and reassembly of the Abu Simbel temples within Egypt. The temples of Kalabasha, Abu Simbel, and Philae were also moved to other locations in Egypt. Four temples were disassembled for shipment and reassembly in museums in developed countries that covered the costs. The National Museum of Sudan received some temples and tombs and parts of the Faras Cathedral. At least twelve temples, the Buhen Fort, cemetery of Fadrus, and an unknown number of artifacts were destroyed by the creation of Lake Nasser (Neher 2012; Wikipedia 2018a). However, little was done to preserve important archeological treasures that will be lost in completion of the Ilisu Dam in Turkey (Box 6).

BOX 6. Archeological Impacts of the Ilisu Dam in Turkey

The Ilisu Dam on the Tigris River will be the largest hydropower dam in Turkey. It is expected to flood 313 km^2, including nearly 90 percent of the City of Hasankeyf (Sevinclidir 2016). It will be the world's largest rock-filled dam in terms of volume and crest length. The 10.4 billion m^3 reservoir will support a 1,200 MW hydropower station.

Hasankeyf was established 12,000 years ago during the Neolithic period as one of the world's first organized human settlements (Arango 2016). It is the only area in Turkey with remnants of Assyrian, Byzantine, Abassidian-Islamic, and Ottoman historical sites in one place (Mitchell 2016). The dam will raise the Tigris at Hasankeyf by 60 meters, submerging 80 percent of the ancient city, including up to 400 historical sites (nearly all still unexplored). The lost heritage will include the largest surviving medieval arch bridge and the remains of mosques, churches, palaces, mansions, schools, a mint, fortress walls and gates, water canals, inns, baths, streets, cemeteries, prehistoric settlements, 6,000 cave dwellings carved into rocks, and associated artifacts.

Inundation will require resettlement of 78,000 people in 200 villages plus 3,000 nomadic people, largely from the Kurdish minority group. When operational, the Ilisu Dam is expected to reduce downstream water levels in the Tigris, increasing salt water intrusion and jeopardizing livelihoods and fragile ecosystems of the Mesopotamian marshes in southern Iraq (a UNESCO world heritage site).

The Ilisu Dam was first proposed in the 1950s, but it was blocked for many years by legal battles and difficulties in securing financing. An international consortium with Balfour Beatty as lead contractor and the Union Bank of Switzerland as the financial agent backed out in 2001-2002 following pressure from an international NGO campaign. In 2006, the Swiss, German, and Austrian export credit agencies agreed to provide loan guarantees and construction began. However, they withdrew their support in 2009 due to the project's failure to meet the World Bank's environmental and social standards. This was the first hydropower project where public export credit support was withdrawn after it had been approved.

The Government of Turkey decided to complete the dam on its own with domestic financing. Construction resumed in 2010. Construction was temporarily suspended in 2014 due to attacks by Kurdistan Workers' Party (PKK) militants. The Ilisu Dam was 96 percent complete at the end of 2017. Construction and inundation are expected be completed in 2018. The government has committed to moving ten historic monuments, but only one was relocated through mid-2017, the mausoleum of the 15th-century warrior Zeynel Bey. It is unclear whether the rest will be moved.

Sources: Banktrack (2015); Gamp (2017); Letsch (2017); Nurol in Media (2017); Soo (2017); Wikipedia (2018b).

3.1.3 HEALTH AND SAFETY RISKS

Hydropower dams can increase the prevalence of some water vector-borne diseases, such as malaria (Smith *et al.* 2013). Yewhalaw *et al.* (2009) found that children living close to the Gilgel-Gibe Dam in Ethiopia had a higher rate of malaria (7.7 percent) than children in more distant villages (4.4 percent), controlling for age, sex, and time of data collection. Higher malaria incidence can lead to higher costs of prevention, treatment, and lost school and work time and productivity. Sokolow *et al.* (2017) estimated that 277-385 million people faced a higher risk of schistosomiasis because dams block the migration of a river prawn that preys on snails that carry this disease.

Improper construction practices or inadequate quality materials can cause dams to fail, with potentially catastrophic effects on human health and safety and the environment. The worst dam failure in history occurred in 1975 when a typhoon destroyed the Bangiao Dam in China. This breach released 492 million m^3 of water that destroyed 61 smaller dams. The floodwaters were as much as 10 meters high and 11 kilometers (km) wide in some areas and traveled at about 50 km/hour. The dam had been designed to withstand a "1,000-year flood," but typhoon Nina brought twice as much rain as the design was supposed to allow. There were over 1,000 millimeters of rain in the first day (120 percent of the typical annual total) and heavy rains continued for three more days. The affected areas had no emergency warning system and approximately 26,000 people died in the flooding. An additional 145,000 people died from the resulting water contamination and famine. Other estimates of the total death toll were as high as 220,000 people Encyclopedia Brittanica 2018).

The 6,400 MW Sayano-Shushenskaya Dam was the largest hydropower dam in Russia. It failed in 2009 when one of its turbines exploded, killing 75 people and spilling 40 tons of stored petroleum products (Hasler 2010). In 2017, Hurricane Maria cracked the Guajataca Dam in Puerto Rico; Hurricane Harvey forced the controlled release of water from the Addicks and Barker dams that flooded several thousand buildings in Houston; and heavy rains overfilled the Oroville Dam in California, forcing an emergency water diversion and evacuations (Smith 2018). The Xe-Pian Xe-Nanmoy collapse in Laos in 2018 is an example of the failure of a partially constructed dam (Box 7). The Mosul Dam in Iraq is an example of poor siting and design decisions that resulted in costly efforts to reduce the risks of a collapse (Box 8).

BOX 7. Collapse of a Dam at the Xe-Pian Xe-Nanmoy Project in Laos

The 410 MW Xe-Pian Xe-Nanmoy Hydropower Project in Laos began construction in 2013 as a joint venture of the Government of Laos, SK Engineering, Ratchaburi Electricity, and Korea Western Power. It was scheduled to begin operating in 2019 under a 27-year concession that would export 90 percent of its electricity to Thailand (Chuwirich and Park 2018).

This project was about 90 percent complete when one of its smaller auxiliary dams (Saddle Dam D) collapsed on July 23, 2018, after days of heavy rains. The engineering firm reported cracks in the dam 24 hours earlier and tried to avert the collapse without success (Chuwirich and Park 2018). The dam failure released 175 billion cubic feet of water (Paddock and Ives 2018). Heavy rains hindered the rescues and recoveries. Laos government media reported 35 dead, 99 missing, 7,995 people displaced, and 13,067 affected in Attapeu Province (Boyle 2018). The collapse also caused devastating floods downstream in Stung Treng Province in Cambodia (Mongabay 2018).

The Government of Laos announced a commission of inquiry with international experts to determine whether poor construction practices caused the collapse. It also suspended new dam projects and stated that it would conduct safety inspections of existing dams in the nearly 50 hydropower projects in operation (Mongabay 2018).

BOX 8. Safety Risks from the Mosul Dam

The Mosul Dam on the Tigris River is 500 km north of Baghdad in Iraq. This dam was completed in 1984 and began operating in 1986. The 113-meter high reservoir, Lake Dahuk, is 3.4 km long and holds 11.1 billion m^3 of water. It has been called "the most dangerous dam in the world" because of its underlying geology and location in a conflict zone (Adamo *et al*. 2017b). The main 750 MW hydroelectric power plant provides electricity for 1.7 million people. There is also an upstream 240 MW pumped storage unit. The reservoir also submerged many archaeological sites

The Mosul Dam was built on bedrock of soluble minerals, including gypsum, marl, and limestone. When water comes in contact with this rock, these minerals dissolve. This process called *karstification* creates holes in the bedrock under the dam that cause an increasing rate of water seepage under the dam. The water seepage makes the dam structure susceptible to irregular sinking and collapse. The water in this reservoir contains high levels of salts and sulfates, which increases karstification (Adamo *et al*. 2017a). The engineers who designed the dam had recommended thorough cement grouting of the foundation before construction. However, this was not done. Instead, to speed construction, there was a 25-meter deep blanket of grout around the foundation and a 150-meter curtain directly below the dam. A gallery for continuous grouting of the foundation was also installed. An inspection soon after operations began found sinkholes forming around the dam and a large amount of water seepage along the banks.

Since 1986, maintenance crews have injected more than 125,000 tons of liquid cement grout to help reduce erosion of the bedrock. This process has continued every year except for as much as 18 months when it was precluded by battles in the area with the Islamic State of Iraq and the Levant (ISIL). However, experts did not view it as an effective long-term solution (Adamo *et al*. 2017a). There is also a serious risk of sabotage or damage due to political conflict. The dam is susceptible to a catastrophic failure with little advance notice.

If this dam fails, large parts of Mosul would be submerged within three hours. Waves of water up to 30-meter high could roll down the Tigris River, affecting Baiji, Tikrit, Samarra, and Baghdad. A five-meter wave could reach Baghdad within four days and could cause more than 1.5 million deaths and leave four million people homeless (Filkins 2017). Adamo *et al.* (2017b) estimated that 6.2 million people could be affected.

In 2016, the Government of Iraq signed a $300 million, 18-month contract with the Trevi Group, an Italian company, for emergency repairs with World Bank financing. An additional 15,000 t of grout was poured into the bedrock. The Government of Italy deployed 450 troops to protect the dam during the work. Subsequent work will still be needed. Other recommendations for reducing the risks from the Mosul Dam include lowering the water level of the reservoir and completing construction of the Badush Dam downstream to regulate floodwaters in the event of a failure (Adamo *et al.* 2017b).

Safety risks can increase with the age of the dam and inadequate investment in maintenance. The American Society of Civil Engineers (ASCE) reported that the average age of the 90,580 dams in the United States was 56 years in 2016. It classified 15,500 of the dams as high hazard potential and another 11,882 as significant hazard potential. It found that 2,170 of the high hazard potential dams were deficient. It could cost $45 billion to repair high hazard potential dams in the United States (ASCE 2017). The ASCE also recommended preparation of emergency action plans for all dams.

The International Commission on Large Dams (ICOLD) has produced many publications on ways to improve dam safety. For example, ICOLD (2017) contains guidelines for safety management during the large dam operations. Other ICOLD publications have addressed proper foundations for dams, concrete specifications for dams; methods for assessing dam safety risks; design and surveillance of dams to reduce seismic risks; evaluation of flood risks; inspection of dams after earthquakes; safety issues in decommissioning dams; the design, surveillance, and rehabilitation of small dams; and the effects of climate change on dams.

3.2 ENVIRONMENTAL AND SOCIAL MITIGATION MEASURES

Some of the other environmental and social impacts of hydropower can be reduced through good practices in designing, sizing, siting, and constructing dams. Changes in dam operations may also be needed such as managing the amount and timing of water flows and flushing sediment from reservoirs. Some impacts can be mitigated by establishing fish spawning sanctuaries elsewhere. Measures to reduce these environmental impacts of hydropower are generally cheaper than trying to restore damaged ecosystem services, habitat, and plant and animal populations and some damage may be irreversible. The ability to implement better environmental practices may depend on national and subnational government policies, regulations, and enforcement capacity; the requirements of financing sources; and the financial returns from hydropower.

Application of the following principles in planning, development, and operation of hydropower can reduce the risk of adverse environmental and social impacts:

Conduct environmental and social impact assessments. Impact assessments should be done early in the planning and design process and conducted at a river basin or regional scale (Pittock 2010). They can identify the need to reduce or mitigate potential negative impacts on the natural and human environment. These assessments require site-specific data. In some cases, more detailed scientific and engineering studies may be needed to develop effective impact reduction or mitigation measures.

Identify loan or bond financing requirements for environmental and social protection. Acceptance of environmental and social protection conditions can open up other sources of financing that are less costly or more flexible and increase the likelihood of successful implementation and sustainability. However, after a facility is operational, the providers of construction financing typically have little or no ability to enforce environmental and social safeguards (McCartney 2009).

Identify good practices, standards, and codes of conduct. Section 3.4 discusses some guidance documents, standards, and protocols for hydropower. However, none have been widely adopted beyond their organization's responsibilities.

Include a broad range of stakeholders in legitimate participatory planning processes to reduce the risk of protests that can block construction, establishment, or operations.

Determine licensing requirements and ensure that designs and plans are in full compliance.

Gather information on relevant, independent certification systems for timber extraction before dam development. The Forest Stewardship Council and other certification systems are in use in forestry. Pittock (2010) recommended increased attention to diverse stakeholder groups in timber certification processes.

Obtain expert advice on technical and operational advances for new facilities or retrofitting (e.g., new tunneling and dam establishment technologies and abrasion-resistant and fish-friendly turbines).

Establish periodic relicensing requirements (typically every 20-30 years) to improve or remove old or underperforming dams. A relicensing process can also inform the design for new dams and operations of other dams. Voluntary operational reviews can provide similar benefits when relicensing is not required.

There are three basic technical approaches to reducing the non-GHG environmental impacts of hydropower dams:

1. Site in locations that do not inundate or block fish passage into the habitats for migratory species;
2. Design the dams to pass sediment and nutrients efficiently; and
3. Operate water flows to maintain a semblance of natural flows.

Table 5 provides examples of how improved siting, design, and operation can reduce the impacts of hydropower dams on fish migration and habitat, trapping of sediment and nutrients, and alteration of natural water flows.

TABLE 5. Siting, Design, and Operation to Reduce the Other Environmental Impacts of Hydropower Dams

Counteract impacts→→ Aspects of project ↓↓↓	Barrier to migratory fish & Innundation of habitat	Trapping of sediments and nutrients	Alteration of natural flows
Siting	1. Above existing barriers to migration Avoid inundation of critical habitat for endemic native species	2. Deeper canyons in headwaters	3. Re-regulation of altered flows for hydropeaking at or below terminal dam
Design	4. Fish pass facilities, low-impact turbines, fish screens	5. Low level or radial gates for discharge	6. Low capacity factors of power-plant to accommodate variable discharges; Pumped storage
Operation	7. Maintain minimum velocities through reservoirs to maintain larval drift	8. Flushing, sluicing, density current discharges	9. Run of River operations

Source: Thomas *et al.* (2018).

Box 9 discusses a master plan for more sustainable hydropower in Laos that included these three types of technical approaches as well as the installation of floating photovoltaic (PV) panels on reservoir surfaces. Although floating PV has a higher capital cost than land or rooftop panel, it is also more efficient in generating electricity because the water cools the panels. Floating PV panels were first used on lakes in France, England, and Japan. Brazil was the first country to install floating PV at reservoir dams. A 1 MW floating photovoltaic system began operating at Brazil's Sobradinho Dam in late 2017, which had only been generating 16 percent of its hydropower capacity due to drought. In 2018, a 5 MW floating photovoltaic system was installed at the Balbina Dam in Brazil, which had only operated at 40 percent of its hydropower capacity between late 2015 and May of 2018 because of droughts (Bloomberg Environment 2017). Portugal's Alto Rabagão Dam installed 220 kW of floating photovoltaic panels at hydropower dams for a different reason -- to help meet the peak demand for electricity (Kaufman 2017).

BOX 9. Master Plan for More Sustainable Hydropower on the Xe Kong River in Laos

The Xe Kong River was the last relatively unobstructed major tributary of the Lower Mekong Basin. It was important for commercial fishing and spawning of migratory fishing and had the second highest aquatic biodiversity in the world (after the Amazon). The Xe Kong River was also the most important remaining source of sediment for the Mekong Delta in Vietnam, one of the three major delta systems in the world most vulnerable to sea level rise that risks submerging human settlements, infrastructure, and agriculture.

The Government of Laos has signed memorandums of understanding for 70 hydropower projects on the Lower Mekong, including 15 that are already completed or under construction. The Xe Kong River is under threat from some of proposed hydropower dams, including seven large dams that would turn the main stem of the river into a series of lakes. A master plan for sustainable power recommended adding floating photovoltaic panels on the surface of existing dams, starting with the largest hydropower reservoir in the basin, the 290 MW Xe Kaman 1 Dam.

Installing photovoltaic panels on 15 percent of the surface of the Xe Kaman 1 Dam could expand the power capacity by 1,200 MW at a cost of $1,000/kW (the unit cost is likely to fall to $900/kW within a decade). Combining hydropower and solar power also reduces the supply intermittency issues associated with both technologies. The sustainable hydropower plan recommended phased installation of floating photovoltaics at other existing reservoirs instead of constructing new dams on the mainstream of the Xe Kong. The existing grid could accommodate an additional 400 MW of power, but would need to be expanded beyond that.

Any additional dams in the basin would be sited at the upper catchment areas of the river, where less sediment would be trapped than at downstream sites. The plan also recommended the following environmental performance criteria for new and existing dams:

1. Establish an upstream and downstream fish passage system that allows a 95 percent survival rate;
2. Encourage larval drift downstream and through the reservoir with a flow velocity of at least 0.3 m/second to maintain fish food supplies;
3. Minimize barotrauma on fish from pressure changes in the power house and spillway;
4. Minimize fish mortality from turbine blade strike and shear;
5. Pass at least 95 percent of suspended sediment as nutrients for fish and agriculture;
6. Maintain reservoir storage capacity
    a. Remove the deposited bed load
    b. Avoid significant deposition in deep pools
7. Minimize the number of people to be relocated after considering the projected 100-year flood (Thomas *et al*. 2018).

In some cases, efforts to reduce or mitigate the environmental and social impacts of very large-scale hydropower may not be effective. Furthermore, the declining costs of solar and wind power and energy storage may make very large hydropower financially and economically uncompetitive. In these cases, it may be preferable to suspend construction of new, large-scale hydropower units as the Government of Brazil did in early 2018 (Box 10).

BOX 10. Brazil's Suspension of New, Very Large Dams in the Amazon

The $18.5 billion, 11,223 MW Belo Monte Dam in Brazil's Amazonia began operating in 2016. At the time, it was the world's third largest dam in capacity. It has reduced the volume of the Xingu River, affecting navigability and fish biodiversity. It also partially flooded the city of Altamira. Belo Monte may be the last of the huge hydropower power dams in Brazil as it and the São Luiz do Tapajós Dam generated enormous opposition from experts, civil society organizations, indigenous populations, and the public (Runyon 2018).

The Luiz do Tapajós Dam was expected to be the second largest hydropower dam in Brazil with an installed capacity of 8,040 MW and a 400 km^2 reservoir. In August 2016, Brazil's environmental agency, IBAMA, later cancelled the environmental license for the proposed dam after the national agency for indigenous affairs, FUNAI, called for demarcation of a 1,780 km^2 area in its vicinity for the Munduruku people. This dam was also expected to have negative effects on fish and bird populations.

In 2017, Brazil issued a ten-year energy plan issued in 2017 that removed mention of two, previously proposed massive dams on the Amazon. This plan dropped the Sao Luiz do Tapajos Dam and the 2,333-MW Jatoba Dam on the same river. These two dams had been expected to account for 70 percent of the country's hydropower generation between 2019 and 2023. The plan did include 15 small- and medium-sized dams with a total capacity of 3,066 MW of capacity by 2026, but only two would be located in the Amazon.

In early 2018, the Government of Brazil shelved plans to build more large-scale hydropower dams in the Amazon basin. Minister of Mines and Energy, Fernando Coelho, attributed the decision to "the difficulty of licensing big dams, the increasingly competitive cost of other renewable energies …and society's need to discuss all major investments in the Amazon…" Suspending plans for additional large-scale hydropower was a major policy change since Brazil already had 1,309 hydropower dams (including 219 with a capacity of 30 MW or more) and obtained 68 percent of its electricity from these dams.

The President of the Energy Research Company under the Ministry of Mines and Energy, Luiz Augusto Barroso, stated that the government would now consider the social, environmental, and cost-benefit ones." He noted that some planned, large dams on the Amazon would have flooded areas in national parks and indigenous reserves. Barroso also observed that the 1) actual costs of large hydropower were often higher than projected, 2) the benefit estimates were frequently based on overly optimistic assumptions, and 3) government subsidies were often required for financing and transmission and distribution costs. Large hydropower was also more complicated than utility-scale wind, solar, or fossil fuel power alternatives (Kepp 2018).

Repowering or re-engineering older dams. System modifications can allow older dams to produce more electricity. Usable reservoir capacity can be restored by removing sediment. Higher capacity generators can be installed at existing hydropower dams. Hydropower generators can be added to dams built for other purposes. Also, pumped storage can be added to reduce the need for more power generation capacity from hydropower or other sources (Pittock 2010).

Decommissioning and removal of unproductive or environmentally damaging dams. In 1999, the Edwards Dam in Maine was removed to restore native fish populations, including an endangered sturgeon species. This was the first time that a dam was removed in the United States for fisheries restoration (Crane 2009).

3.3 IMPACTS OF CLIMATE CHANGE ON HYDROPOWER

The potential impacts of climate variability and climate change should be considered in the design, analysis, and operations of new and existing hydropower installations. This includes normal seasonal

weather patterns and climate variability from recurring phenomena, such as the El Nino and the La Nina Southern Oscillations. Since hydropower facilities have long expected lives, climate patterns may not remain the same over this timeframe.

The impacts of climate variability and change on hydropower differ for reservoirs and run-of–river dams. Effects also depend on local geomorphology, hydrology, land uses, and vegetative cover. Run-of-river dams generate less hydroelectric power during low dry season water flows or high rainy season flows that cannot be captured. Global warming can increase the frequency and magnitude of droughts and extreme rain events, but the effects are difficult to predict in specific locations. Some areas may have less total rainfall and longer and more severe droughts. Some areas may have higher total rainfall, but it may be concentrated over a shorter period due to more extreme rainfall events. Some areas could see more droughts as well as more floods at different times of the year. Higher temperatures also increase water evaporation from reservoir dams, reducing the effective storage capacity (Beilfuss and Triet 2014).

Prolonged droughts can substantially decrease the amount of hydropower that can be generated over a year or multi-year period, causing cash flow and loan repayment problems for specific facilities. Countries with a high reliance on hydropower may face national shortages of electricity during severe droughts. World hydropower generation has declined over 5 percent in major drought years compared to the long-term average (Van Vliet *et al.* 2016).

FIGURE 3. Cantareira Reservoir in Brazil Under Drought Conditions

Source: Flickr/Fernando Stankuns.

Potential climate change impacts on hydropower at the global level include

- **Glacial melt:** Hydropower dams on rivers with increasing flows from glacial melt may be able to generate more electricity if the reservoirs are large enough to hold the additional water. This may be the case for the Canon del Plato dam in Peru. Some run-of-river systems may also be able to handle higher than usual water flows from glacial melt. However, after the glaciers have been fully

melted, there may be less water for hydropower generation in the future. Year-round operation may no longer be possible if winter snow accumulation is insufficient to keep enough water flowing to dams during the summer.

- **Increased precipitation:** Higher precipitation can increase stream flows in some watersheds, allowing more hydroelectric power generation if the reservoirs can accommodate the larger volume of water. After the reservoir capacity has been reached, there would be no benefit from additional water flows. More precipitation would not benefit run-of-river systems that experience higher peak flows without a longer duration of the flows because the additional water cannot be used.
- **Decreased precipitation:** Lower precipitation may reduce stream flows for hydropower production in some watersheds. This could have a large effect on the financial and economic viability of run-of-river and reservoir-based hydropower.
- **Increased evaporation:** Higher temperatures increase evaporation from reservoirs, reducing the availability of water for hydropower during normal dry seasons and droughts.
- **Change in the proportions of snow and rain:** Higher global temperatures may increase the proportion of precipitation falling as rain rather than snow in some climates and elevations. Since snow often melts gradually, it increases the persistence of high stream flows over a longer period than rain. This is especially true if much of the rain falls in high-intensity events that cause more land flooding. A change in the proportions of snow and rain can affect the magnitude and timing of peak and average stream flows in run-of-river and reservoir hydroelectric systems. However, snowfall patterns are complex and variable. Global warming could lead to less frequent or smaller snow events in some areas and have the opposite effects in others.
- **Increased sedimentation:** As sediment-rich water flows into a reservoir, the sediment precipitates out as the water slows and is deposited behind the dam. High-intensity rainfall makes water flow faster so it can pick up more sediment over land and reduce sediment absorption by the soil before the water reaches the reservoir. Increased sediment deposition from extreme rainfall events can substantially reduce the effective storage capacity of a dam for hydropower generation and the service life of the reservoir and turbines.

  Sedimentation may make more frequent dredging and flushing of the reservoir necessary and these processes are costly and only partially effective. Many pre-investment analyses of large, hydropower dams in the tropics have greatly underestimated the actual sedimentation rates that have occurred. The shorter lifetime and higher maintenance and replacement costs due to greater sedimentation can substantially reduce the financial and economic returns of hydropower.
- **More frequent, longer, or more extreme droughts:** Droughts reduce water flows for electric power generation, and global warming may increase the prevalence and magnitude of droughts. Droughts may reduce the actual financial and economic benefits of hydropower below the expected levels. Droughts may also have other economic and environmental impacts when there are also more extreme rainfall events. For example, some clay soils swell with water and shrink and crack as they dry out, damaging dams, buildings, roads, and trees and vegetation. Longer dry periods can make these soils less absorbent so that they yield more sediment when rains occur.

Modified Operations for Flood Control: Hydropower reservoirs can sometimes be managed to reduce or offset changes in flood frequency, severity, or timing. Global warming can increase flood risks in some locations, but the effects on river flows are difficult to predict and depend on whether the reservoirs also serve flood control and irrigation purposes. Hydropower dams are sized and managed to store and gradually release excess water flows can reduce downstream flood damage. If the reservoir is not large enough, heavy rains may make it necessary to release excess water without generating electricity to avoid damage from accidental overtopping of dams.

Global estimates of impacts of climate change on hydropower are not sufficient for decision making on specific facilities. The local impacts vary with their geography, dam characteristics, local and regional climate changes, and the biophysical context. Edenhofer *et al.* (2011) reviewed the small number of available studies on the effects of climate change on hydropower. They concluded that global hydropower production could increase slightly, but there may be negative impacts in particular countries or regions that may experience more frequent or more severe droughts. It is difficult to predict how global climate change will affect precipitation patterns at the country and subnational levels because the various general circulation models have produced very different projections of the effects of global warming on the magnitude and timing of precipitation at a local level (Hamududu and Killingtveit 2012).

The World Bank commissioned the Potsdam Institute for Climate Impact Research and Climate Analytics to model the effects of global warming on agricultural production, water resources, ecosystem services, and coastal vulnerability. The model included three scenarios for global warming—the current 0.8°C increase over pre-industrial temperatures as well as 2°C and 4°C increases. The analysis was disaggregated by regions. It projected that Southeast Asia would face a higher magnitude and frequency of extreme rainfall events as well as an increase in the length of droughts (World Bank 2013). The Mekong Regional Commission had assumed that climate change would increase river flows and hydropower potential in the Lower Mekong Basin, but this assumption does not appear to be valid if the Potsdam Institute's modeling is correct. World Bank (2013) also presented the modeling results for Sub-Saharan Africa and Southeast Asia. World Bank (2014b) discussed the modeling results for Latin America, the Middle East, and North Africa.

The impacts of climate variability and change vary with the type of hydropower system:

- **Run-of-river dams:** Run-of-river dams are directly affected by changes in stream flows due to weather and climate change impacts. Intense precipitation events will lead to overtopping of these dams and foregone electric power generation. Even short droughts or dry seasons are likely to substantially reduce electricity production.
- **Reservoir dams:** Hydropower facilities with reservoirs are less susceptible to changes in stream flows than run-of-river dams since they can be managed to reduce the impacts of changes in rainfall and snow or glacier melt. However, serious droughts or extreme rains can have major effects on hydropower generation and lead to national shortages of electricity in countries highly dependent on hydropower (Bakke 2016).
- **Pumped storage dams:** Pumped storage dams are filled when surplus electricity that would otherwise be curtailed or could only be sold at a low price is available to pump water uphill. This water is released for hydropower production later when supplies are needed to respond to peak demand or shortfalls in supplies from other sources. As a result, pumped storage is less likely to be affected by climate variability than reservoir dams.

Managers of hydropower dams have begun to integrate climate change risks in electric power planning. Hellmuth, Cookson, and Potter (2017) proposed a four-part approach to addressing climate change in hydropower planning: 1) assessment of climate risks and vulnerabilities; 2) identification, evaluation, and prioritization of options to address climate risks; 3) integration of climate change considerations into project implementation, power planning, and operations and maintenance; and 4) monitoring, evaluating, and adjusting plans over time. It may be possible for owners of hydropower dams to obtain weather-indexed insurance to reduce losses from extreme weather, but this parametric insurance is costly.

Due to the uncertainty in the effects of climate variability and climate change on hydropower, financial and economic analyses and plans should consider multiple scenarios with probabilistic simulations (Monte Carlo analysis) or new methods for improving decisions under deep uncertainty (Hallegate *et al.* 2012). It may also be possible to reduce financial risks from major droughts by purchasing weather-indexed insurance for hydropower facilities.

3.4 COMMON IMPACT ASSESSMENT GUIDELINES OR PROTOCOLS FOR HYDROPOWER

Multilateral development banks, donors, and public export financing agencies in developed countries have provided a substantial share of the financing for large-scale hydropower in developing countries. Some of these investments have raised major concerns about environmental and social impacts. Multilateral development banks have continued to view hydropower as an important tool for increasing development, combating climate change, and improving food and water security. The World Bank (2014a) estimated that only a modest fraction of the hydropower potential of the developing world has been tapped. The Asian Development Bank (2016) noted that hydropower can help countries achieve economic growth while meeting their carbon mitigation commitments under the Paris Agreement.

Better environmental and social and impact assessments and more effective involvement of a broad range of stakeholders can help reduce problems before and after the establishment of new hydropower systems. There have been some attempts to standardize information collection on the social and environmental impacts of hydropower. However social impact assessment tools have been hampered by a lack of accepted indicators and data and measurement challenges (Tilt *et al.* 2009).

There are various standards or guidelines for assessing and mitigating the environmental, social, and economic impacts of hydropower and other infrastructure:

1. International Hydropower Association (2006, 2010) Hydropower Sustainability Assessment Protocol;
2. World Commission on Dams (2000) Strategic Priorities and Guidelines;
3. International Finance Corporation (2012) Performance Standards on Environmental and Social Sustainability;
4. World Bank Environment and Social Framework (2018); and
5. Guidelines to Reduce Hydrological Uncertainty in the Design of Small-Scale Hydropower (Cordova and Camacho 2018).

Use of these standards and guidelines can improve the planning, design, and operation of hydropower dams. However, hydropower investments in developing countries are increasingly being funded by Chinese banks, government agencies, and companies, rather than multilateral finance institutions and other bilateral donors and trade promotion agencies. Tilt and Gerkey (2016) reported that Chinese firms were involved in planning or constructing over 300 dams in 70 countries. China's looser standards for social and environmental impact assessment and mitigation are becoming the predominant standards for new construction of large-scale hydropower in developing countries.

3.4.1 HYDROPOWER SUSTAINABILITY ASSESSMENT PROTOCOL (HSAP)

The International Hydropower Association first published the Hydropower Sustainability Assessment Protocol in 2006 and it was revised in 2009 and 2018. This tool was designed to assess the sustainability of individual hydropower projects, regardless of their type, scale, and other reservoir uses. It can be used for storage, run of river or pumped storage. The 2018 version is available in English, Chinese, French, Portuguese, Russian, and Spanish (http://www.hydrosustainability.org/Hydropower-Sustainability-Assessment-Protocol/Hydropower-Sustainability-Assessment-Protocol/The-Protocol-Documents.aspx).

The HSAP addresses potential impacts in the four stages of hydropower development: 1) early stage screening, 2) preparation (including design and licensing), 3) implementation (construction through commissioning), and 4) operation. There are nine topics for the early stage screening, 24 on preparation,

21 on implementation, and 20 on implementation. The early stage screening is not scored since it is intended as guidance (IHA 2018). There is an online knowledge base to assist users at http://www.hydropower.org/sustainable_hydropower/HSAF.html.

Each topic in the other three stages is scored on a five-point scale based on specified criteria. There are six criteria for the scoring statements on each topic: Assessment, Management, Stakeholder Engagement, Stakeholder Support, Conformance/Compliance, and Outcomes. A score of one is assigned when there are significant gaps from basic good practices. A score of two indicates that most basic good practices have been undertaken with one significant gap. A score of three is appropriate when all basic good practices have been used. A score of four is given if all basic good practices have been carried out or exceeded, but there is at least one significant gap in the requirements for best practices. A score of five indicates that all identified best practices have been followed.

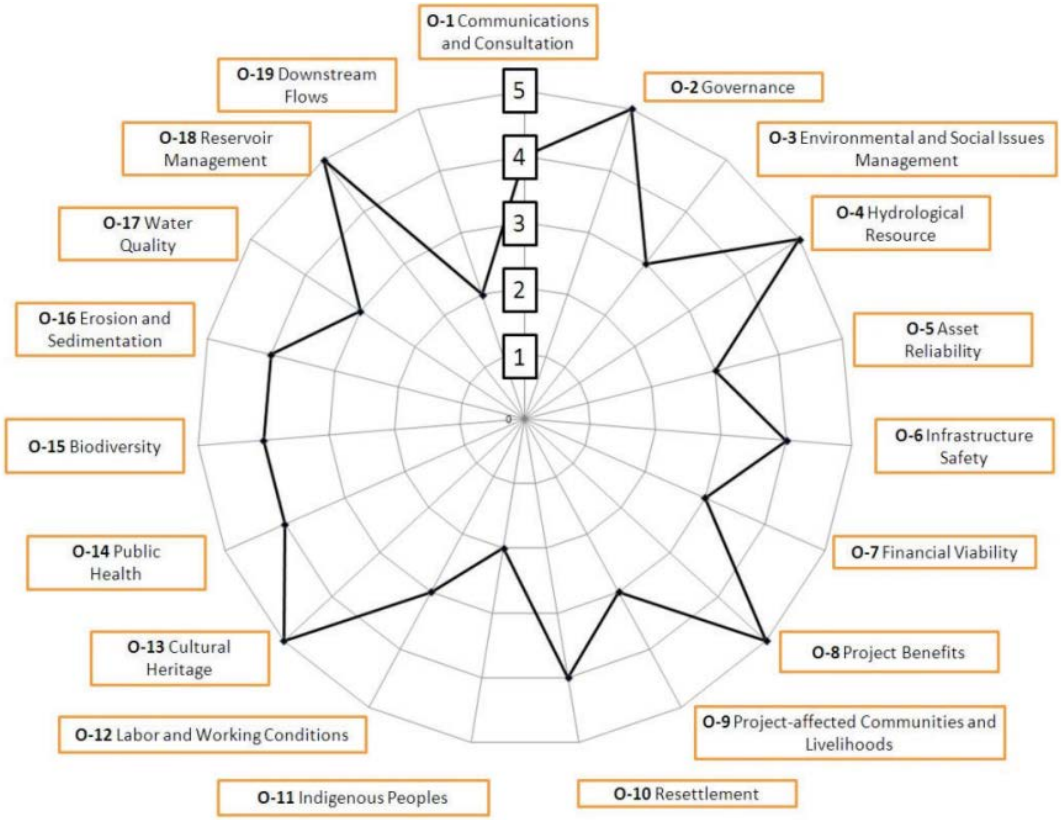
The HSAP lists criteria for each score specific to each topic. For example, preparation of a plan to identify and reduce water quality risks is a basic good practice for site preparation. The recognized best practice would be anticipating emerging risks and opportunities and addressing water quality impacts beyond those caused by the hydropower facility. Objective evidence is required to support the scoring.

HSAP scores are shown separately for all dimensions through a spider diagram for each of the three stages that are scored. The spider diagram shows each of the strengths and weaknesses. Figure 4 contains an example of a spider diagram for the operations stage.

The HSAP does not recommend calculation of a total score. As a result, there is no cut-off score for deciding whether a hydropower proposal should be approved, modified, or rejected. International Rivers (2008) recommended using a weighted average of the individual HSAP scores as a summary measure. However, reliance on either an average or total score could obscure the fact that a proposal has a low score on one or more important dimensions. If an average or total score is used, developers and decision makers should consider whether low scores on any dimension should be mitigated.

The HSAP called for assessing impacts on water availability and reliability, including upstream hydropower operators, future water and land resource development, catchment conditions, and climate change. It recommended designing hydropower facilities to reduce exceptional greenhouse gas emissions from reservoirs. However, the HSAP does not require an assessment of GHG emissions from reservoirs.

FIGURE 4. Sample Spider Diagram From the Hydropower Sustainability Assessment Protocol for the Operations Stage



Source: Liden and Lyon (2014).

Liden and Lyon (2014) concluded that the HSAP assessors needed training to ensure quality and consistency because the guidance is complex. They found that the HSAP definitions of basic good practices did not reflect typical practices in many countries and may be difficult to achieve. They viewed the HSAP as useful for providing benchmarks and identifying areas for improvement, but not for comparing the sustainability of different proposals, especially across countries. They did not consider the HSAP to be a sufficient alternative to the World Bank's policies and procedures, but noted that it could be useful in improving hydropower proposals when used together with the World Bank guidance.

REN21 (2018b) reported that Sustainable Energy for All and the International Hydropower Association signed an agreement in late 2017 to develop a Hydropower Preparation Facility. This facility use the HSAP tool and help national governments set priorities for potential hydropower projects based on their assessed sustainability before issuing tenders.

3.4.2 WORLD COMMISSION ON DAMS SYNTHESIS GUIDE

The World Bank and the International Union for Conservation of Nature (IUCN) established the World Commission on Dams (WCD) in 1998 in response to concerns about large dams. The commission issued guidelines for hydropower development and analysis (World Commission on Dams 2000). The guidelines called for a life cycle assessment (LCA) of hydropower and its alternatives (including a no dam

alternative). The life cycle assessment would include impacts on land, air, and water resources, GHG emissions; sustainability of local livelihoods; legal and regulatory compliance, and public acceptance.

The WCD guidelines called for estimates of the net GHG emissions from hydropower, including emission changes associated with hydropower generation and the impoundment versus the baseline. It also suggested modeling long-term hydrological changes and variability due to climate change and analyzing the resulting economic risks. The WCD guidelines addressed issues that were not well covered by other guidelines and standards at the time, and were more specific and e stringent than the HSAP (International Rivers 2008; Wenban-Smith 2010).

The WCD guidelines are voluntary and there is no entity overseeing their use in general. However, the European Union (2004) required compliance with the WCD guidelines for hydropower facilities greater than 20 MW that planned to sell carbon credits in the European Union Emissions Trading Scheme. International Rivers (2010) proposed revisions to the WCD guidelines and discussed case studies where the WCD principles were or were not applied. However, International Rivers did not specifically address GHG emissions from dams.[1]

3.4.3 IFC PERFORMANCE STANDARDS ON ENVIRONMENTAL AND SOCIAL SUSTAINABILITY

The International Finance Corporation (IFC) issued Performance Standards on Environmental and Social Sustainability These performance standards build on a variety of environmental and social policies and guidance issued by the IFC in the mid-1990s. The performance standards were last updated in 2012. They address the assessment and management of environmental and social risks, including labor and working conditions, biodiversity conservation, resettlement, and treatment of indigenous populations. Since January 1, 2012, the IFC has required use of these standards for all investment and advisory clients for all types of infrastructure.

The IFC performance standards require analysis of alternatives such as different locations, technologies, or capacity levels. They also call for implementation of technically and financially feasible options to reduce GHG emissions, including use of renewable or low-carbon energy sources. They require identification of potential impacts on ecosystem services that may be exacerbated by climate change and adoption of mitigation measures if the impacts are unavoidable. The IFC performance standards included specific requirements for assessing and addressing GHG emissions, but they were not impacts specific to hydropower. Consequently, they did not provide guidance on estimating the GHG emissions from reservoirs or the impacts of climate change on dams.

3.4.4 WORLD BANK (2017) ENVIRONMENTAL AND SOCIAL FRAMEWORK

In 2017, the World Bank issued a new environmental and social framework for investments that it finances. Use of this framework will be mandatory in 2018. The framework included 1) a vision for sustainable development, 2) an environmental and social policy for investment project financing, and 3) environment and social standards. It contained ten environment and social standards:

1. Assessment and management of environmental and social risks and impacts;

[1] International Rivers is an international nongovernmental organization network of people potentially affected by dams and grassroots organizations, environmentalists, and human rights advocates.

2. Labor and working conditions;
3. Resource efficiency and pollution prevention and management;
4. Community health and safety;
5. Land acquisition, restrictions on land use and involuntary settlement;
6. Biodiversity conservation and sustainable management of living natural resources;
7. Indigenous peoples and Sub-Saharan African historically underserved traditional local communities;
8. Cultural heritage;
9. Financial intermediaries; and
10. Stakeholder engagement and information disclosure.

The World Bank will issue additional directives, procedures, guidance, and information tools to support the framework. Investments will be required to apply relevant general and industry-specific environmental, health, and safety guidelines and examples of good international industry practices. Affected parties will have access to headquarters and local grievance mechanisms and the World Bank Inspection Panel.

The 2017 environment and social standards contained an annex on dam safety. It defined large dams as reservoirs with a height of 15 meters or more or a height of 5-15 meters and an impoundment volume of more than 3,000,000 m^3 of water. It also set requirements for small dams with potential safety risks due to floods, high seismicity, complex foundations, retention of toxic materials, or significant downstream impacts, or that are expected to become large dams during their operating life.

An independent panel of at least three experts and the proposed World Bank borrower will review the design, construction, and start of operations for new, large dams and new, small dams with high safety or environmental risks. The proposed borrower will nominate the experts, who will be approved and contracted by the World Bank. Detailed plans for construction supervision and quality assurance, instrumentation, and operations and maintenance will be required for these dams. After completion of the dams, the World Bank will require periodic safety inspections and implementation of measures to address safety deficiencies. Bidders for dam development will need to be prequalified for procurement and tendering.

When a proposed World Bank project depends on the performance of an existing dam or one already under construction, the borrower will have to arrange for independent experts to inspect the safety of the dam and its appurtenances, review the operation and maintenance procedures, and recommend remedial work or safety measures. A previous dam safety assessment or recommendations for safety improvements can be used if an effective dam safety program is in place and the World Bank concurs that inspections have been satisfactory and documented. New dams and existing or partly constructed dams with high hazards that require significant or complex remedial work will need to be reviewed by a panel of independent experts.

Dam safety reports will be required for new, existing or partly constructed dams. They will need to include 1) a plan for construction supervision and quality assurance; 2) an instrumentation plan for monitoring dam behavior and hydrological, meteorological, structural, and seismic factors; 3) an operation and maintenance plan; and 4) emergency preparedness plan.

3.4.5 GUIDELINES TO REDUCE HYDROLOGICAL UNCERTAINTY FOR SMALL-SCALE HYDROPOWER

Good practices in conducting assessments and planning can help avoid cost over-runs, improve the likelihood of achieving expected benefits, and reduce the environmental and social impacts of hydropower. Cordova and Camacho (2018) noted some common risks of small-scale hydropower in developing countries:

1. Oversized design capacity that cannot be achieved;
2. Unanticipated land use changes that affect future hydrological flows;
3. Failure to consider the effects of erosion and sedimentation on the useful life of intake infrastructure and reservoirs;
4. Inadequate hyetograph calculations to plan for the effects of extreme storms on the design and size of spillway structures; and
5. Failure to consider the minimum water flows needed to maintain the river flows and other water uses.

Good practices in conducting hydrological assessments and planning can help avoid capital and operation and maintenance cost over-runs, improve the likelihood of achieving the expected benefits, and reduce negative environmental and social impacts of hydropower.

Cordova and Camacho produced guidelines for assessments and planning for small-scale hydropower (defined as less than 10 MW). These guidelines addressed the collection, analysis, and presentation of climate, soil, geomorphological, administrative, land use, and land cover data, including mapping of basins and sub-basins. The guidelines discussed scenarios for estimating water flows, design discharge under the usual climate and extreme flood events, and sediment loads. They also issued recommendations for hydrological models and handling uncertainty.

4. FINANCIAL AND ECONOMIC BENEFITS AND COSTS

This section presents the findings of a literature review on the financial and economic benefits and costs of hydropower dams. It begins with a brief summary of key concepts in cost-benefit and cost-effectiveness analyses. The chapter also discusses the potential for energy efficiency to reduce the demand for hydropower.

4.1 COST-BENEFIT ANALYSIS CONCEPTS

4.1.1 FINANCIAL ANALYSIS AND ECONOMIC ANALYSIS

Cost-benefit analysis includes financial analysis and economic analysis, which are similar but reflect different perspectives. *Financial analysis* considers the monetary costs and benefits to hydropower system owners and other investors and the sustainability of operations. It includes the value of subsidies received by the owners and investors and their costs for taxes. Financial analysis addresses the incentives for a private sector investment and its potential sustainability. It may also be needed for regulatory approvals and mitigation or compensation plans.

E*conomic analysis* takes the broader perspective of the impacts on the national economy -- Gross Domestic Product (GDP). This addresses the costs and benefits for a broader set of national stakeholders. The economic analysis does not count subsidies (or taxes) since the benefits (costs) to the owners are offset by the costs (benefits) to the government. An economic analysis may also consider the monetary value of some environmental and social benefits and costs. It may also quantify or qualitatively discuss environmental and social benefits and costs that are difficult to value in monetary terms.

4.1.2 NET PRESENT VALUE AND DISCOUNTING

In both financial and economic analyses, the *present value of net benefits* (*net present value*) is calculated to account for the time value of money. Costs and benefits in future years have a lower value than costs and benefits now because positive returns can be obtained from investments, even if there is no monetary inflation. The *discount rate* is the adjustment factor used to compare differences in the value of money over time. When a **real** discount rate (above the inflation rate) is used, future costs and benefits are estimated in *nominal* monetary values (current monetary values unadjusted for inflation).

In comparing the findings of different cost-benefit analyses, it is important to compare the discount rates used because they can make a large difference in the net present values. A high discount rate gives less weight to costs and benefits in future years. A high discount rate is less favorable for investments in large-scale hydropower that have high initial capital costs, long time lags before benefits begin, and benefits that continue over a long period of time. However a high discount rate also diminishes the value of environmental or social impacts that continue over a long time or occur in the future.

Different discount rates may be appropriate for financial and cost-benefit analyses. The discount rate for a financial analysis reflects the owners' cost of financing (effective interest rate). There are three alternative approaches for defining a discount rate for an economic analysis. One approach that is sometimes used is the cost of government borrowing, but this can vary a lot and be manipulated

through government policies. Most economists prefer one of the other two approaches below. The *opportunity cost of capital* in the economy is often much higher than the cost of government borrowing since it reflects the potential returns on private and public investment. The *social rate of time preference* reflects the tradeoffs between consumption of present and future generations. It is often considered to be lower than the opportunity cost of capital.

World Bank (2015) guidelines for economic analysis of power sector projects required a real (inflation-adjusted) discount rate of 12 percent. USAID's *Cost-Benefit Analysis Guidelines* (2015) also used a 12 percent real discount rate for economic analyses. However, the USAID guidelines also recommended a sensitivity analysis showing the effects of different discount rates on the economic net present value. For financial analyses, USAID (2015) recommended using the interest rate on loans that could be obtained by the developers or beneficiaries.

4.1.3 TYPES OF HYDROPOWER COSTS AND BENEFITS

Table 6 lists some direct and indirect costs and benefits of hydropowe.

TABLE 6. Direct and Indirect Benefits and Costs of Hydropower

	Benefits	Costs
Direct	• Electricity sales or direct use (including pumped storage, grid balancing, and black start capabilities) • Flood control • Storage and management of water supply for drinking, sanitation, livestock, irrigation of crops, and commercial and industrial use	• Engineering, siting and planning • Land acquisition and preparation • Dam construction and inundation • Turbines and other equipment • Operation, maintenance, and replacement • Decommissioning • GHG emissions from construction (fuel, manufacturing materials, land clearing) • GHG emissions from reservoir establishment and dam operations • Resettlement costs and increased poverty from population displacement or resettlement • Increased incidence of malaria and other diseases
Indirect	• National or subnational economic growth • Health • Food security • Poverty alleviation	• Loss or damage to ecosystem services (forest productivity, carbon sequestration, fish populations, water quality, and biodiversity) • Adverse effects on health. social outcomes, political stability, and human rights

Sources: IEA and Republic of Brazil (2012); Intergovernmental Panel on Climate Change (2011); Tilt *et al.* (2009); McCartney (2009); Pittock (2010).

The value of the electricity that can be sold or used directly is largest economic benefit from hydropower. The usable electricity can be less than the amount generated because water may need to be pumped out of the reservoir when the quantity of electricity demanded is less than the amount generated. Unless there is a fixed price contract, the price of electricity sold to the grid can vary with the time of day, season, and other factors affecting the demand and supply of all sources of electricity. The price of hydropower delivered to the grid can be zero or below the variable costs of hydropower generation. At times, the grid may need to curtail purchases of electricity. Storage of surplus hydropower in batteries is not yet commercially viable, but may be in the future as their costs decrease.

A financial analysis considers the revenues that a hydropower generator receives from sale of the electricity. Electricity rates are often regulated or subject to price controls and may vary by type and

location of the customers and their usage levels. In some cases, the allowed rates are below the cost of production, transmission, and distribution and governments may provide direct or indirect subsidies to generation, transmission and distribution companies. The revenues in a financial analysis may include the value of subsidy payments from the government. Conversely, if the hydropower generator is subject to taxes, the net revenues in a financial analysis would be after taxes.

An economic analysis reflects the costs and benefits to the national economy. Subsidies that governments pay electricity generators are not counted as benefits and tax payments by generators are not counted as costs. Often, the economic benefits include are defined to include consumer surplus. *Consumer surplus* is the difference between the total amount that people are willing and able to pay for a particular quantity and quality of a good or service and the total amount that they actually have to pay (*market price*). The consumer surplus is the area below the demand curve above the equilibrium market price. Consumer surplus is important in an economic analysis as a component of the economic benefits from electricity use in addition to the producer surplus (profits of power generation companies. However, consumer surplus is not included in a financial analysis since it is not a cash flow to consumers.

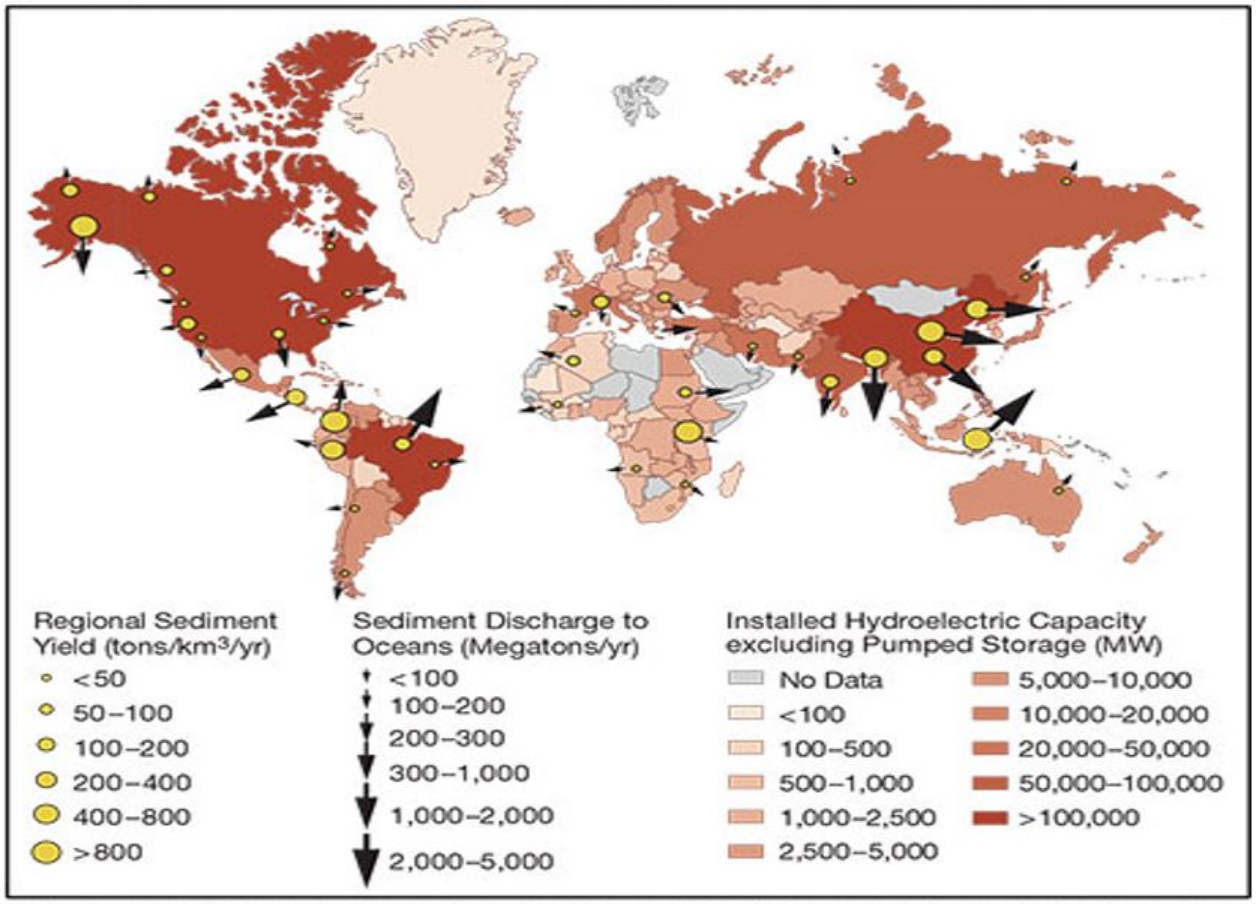
The second largest benefit is the ability to control river flows for water supply and flood control in reservoir dams. Reservoir dams can be managed to capture heavy rainfall and reduce the risk of flooding that can damage infrastructure and urban settlements. Reservoir dams can also store water to even out intra-annual and inter-annual variability of river flows, reducing the effects of droughts on water supply. Run-of-river hydropower facilities do not provide these other benefits associated with reservoirs.

A third major benefit of hydropower is more flexible electric power systems. Reservoir dams can provide *spinning reserves*, electric power to fill gaps between grid demand and supply. Spinning reserves are particularly valuable on grids with significant generation from intermittent wind and solar power.

Some of the surplus hydroelectric power can be recovered for later sale through pumped storage. These systems use surplus electricity at times of low demand to pump water to a higher reservoir. Later, when the demand for electricity is higher, this water is released and used to generate more hydroelectricity. Pumped storage can increase the total value of hydroelectric power sales. Alternatively, battery storage of surplus hydroelectric power may become commercially viable in the future as its costs decrease. Reservoir hydropower requires much less electricity to restart than thermal or nuclear power plants. This makes them useful as a *black start* source to help restore electric power generation, transmission, and distribution after system outages.

As a result of sedimentation, the useful life of a hydropower dam is often far shorter than the projected life. Sedimentation also reduces the amount of power that can be generated during the useful life below the planned levels. As a result, the financial and economic benefits can be much lower than anticipated. About 0.5 to 1.0 percent of the global reservoir volume is lost annually due to sedimentation. If these rates continue, half of the world's reservoir storage would be lost in the next 50 to 100 years. Figure 5 shows that sedimentation yields are often relatively high in developing areas with substantial existing hydropower (China, South America, and Northern India) or high untapped potential (Southeastern Africa and Central America).

FIGURE 5. Hydropower Potential and Sediment Production



Developing regions of the world that stand to benefit most from production of hydroelectricity are often those with the highest sediment yields.

*Installed capacity data and sediment yield data adapted from International Hydropower Association 2015 Hydropower Status Report, figure adapted[16]

Source: Schellenberg *et al.* (2017).

Some dams have had much higher than average rates of sedimentation. The Dez Dam in Iran lost 30 percent of its reservoir capacity in 18 years due to sedimentation (1.47 percent per year, with compounding). About 7 percent of the lost storage volume was recovered in 1980 by flushing the dam. The Sanmenxia Reservoir in China lost about 1.7 percent of its reservoir storage per year (Samadi-Boroujeni 2012).

Box 11 discusses two conflicting cost-benefit analyses of the same proposed hydropower projects in the Lower Mekong Basin.

Box 11. Two Cost-Benefit Analyses of Hydropower in the Lower Mekong Basin

The Mekong River Commission prepared a cost-benefit analysis of four scenarios of dam development in the Lower Mekong Basin (Mekong River Commission 2011). The largest estimated cost was for dam construction. The second largest estimated cost was the reduced value of the downstream river fish catch. The analysis also estimated the costs of reduced production from forests and dry-season, flood-recession rice. Other costs that were not quantified in monetary terms included reductions in the wetlands area, water flows into Tonle Sap, sediment deposition on crop land, and marine fisheries catch. The Mekong River Commission (2011) estimated that the livelihoods of almost a million vulnerable people would be at some risk.

The largest benefit in all of the scenarios was the value of hydroelectric power. The analysis assumed that all of the hydropower benefits accrued to the country where the power was generated. Other benefits included increases in irrigated agriculture, fishing and aquaculture in new reservoirs, and flood mitigation. This analysis concluded that the largest share of the projected benefits was in Laos although benefits were also anticipated in Thailand, Cambodia, and Vietnam.

The Mekong River Commission (2011) analysis concluded that all four scenarios had a positive net present value (NPV) at a 10 percent discount rate. Scenario II involved construction of 11 dams and had a total NPV of $33.4 billion. This included component NPVs of $32.8 billion from hydropower benefits, $0.9 billion from irrigated agriculture and flood mitigation, $0.3 billion from aquaculture in new reservoirs, $0.2 billion from fish catches in new reservoirs, $0.1 billion in wetland benefits, no social mitigation costs or economic losses from sediment and nutrient reductions, and a negative $1.9 billion from reduced wild fish catches.

Kubiszewski *et al*. (2012) criticized the Mekong River Commission (2011) analysis assumptions on the value of reduced fish and aquaculture production, lost ecosystem services, and the discount rate, and argues that appropriate consideration of uncertainty and possible discount rates indicated that the possible net benefit of the proposed development may be negative. They concluded that changing the discount rate and other key assumptions could reduce the NPV from a positive $33 billion to a negative $274 billion. Knowles (2014) also identified many costs that had not been considered in the analysis, including impacts of resettlement and reduced tourism.

Intralawan, Wood, and Frankell (2017) conducted a new analysis of the same hydropower projects using the same 10 percent discount rate. They found a negative NPV of $7.3 billion. This included component NPVs of $6.6 billion from hydropower, $3 billion from other benefits, negative $13.0 billion in reduced wild fish catches, negative $1.6 billion due to social mitigation costs, and negative $2.3 billion in sediment and nutrient losses. The net hydropower benefits were much lower than previously estimated because the Mekong River Commission (2011) used unrealistically low capital costs, electricity prices that were too high, and a flawed model of the market for the electricity. The later analysis also concluded that only 30 percent of the hydropower benefits occurred in the countries where the power was generated. The other 70 percent of the hydropower benefits accrued to the countries that funded the investment or imported the electricity. Thailand would be the main country benefiting and the net economic in Laos would be negative for much of the concession period.

Consequently, Intralawan, Wood, and Frankell (2017) recommended

1. Delaying construction of other mainstream dams until the Xayaburi Dam was completed and the effectiveness of the fish pass and sediment sluice gates was determined;
2. Requiring the full cost of social and environmental mitigation measures to be included in the capital investment requirements for hydropower;
3. Re-assessing the net economic impact and benefits to Laos based on the subset of hydropower projects with a high probability of moving forward; and
4. Developing a new energy strategy for the Lower Mekong Basin based on updated forecasts of electricity demand, lower hydropower profitability, and prospects for energy efficiency and renewable energy.

4.2 COST EFFECTIVENESS OF HYDROPOWER VERSUS OTHER POWER GENERATION TECHNOLOGIES

The *levelized cost of electricity* (LCOE) is the present value of the unit cost of electricity over the expected lifetime of any generating asset. It is a proxy for the average price that the generating asset must receive to break even over its lifetime. The LCOE is commonly used to compare the cost-effectiveness of different electricity generation technologies.

The LCOE includes the costs of planning and design, studies and regulatory approvals, construction labor and materials, equipment purchase and installation, operation and maintenance, and financing (*discount rate*). The LCOE excludes transmission and distribution costs, even though new or expanded hydropower installations may require new grid connections. Grid connection costs may be high for hydropower sites in remote areas or difficult terrain. The LCOE includes social compensation and environmental mitigation costs that power generators have to cover.

However, the LCOE does not include the costs of negative social or environmental impacts borne by others. If requirements for social compensation and environmental mitigation for large-scale hydropower have increased over time, historical cost data for large-scale hydropower adjusted for inflation may underestimate current costs. Decommissioning costs for hydropower dams are usually excluded from the LCOE since few dams have been decommissioned and decommissioning costs in the distant future have a negligible effect on the LCOE after discounting.

Many hydropower facilities have additional purposes besides electricity generation. When there are multiple purposes, *separable costs* that can be specifically attributed to the other uses are estimated and left out of the LCOE calculation. In addition, part of the *joint costs* of the system are allocated to the other uses and excluded from the LCOE, but the costs allocated to each use should not exceed the projected benefits from that use.

Other factors that can have a major effect on the LCOE are the type and scale of the system, expected lifetime, discount rate, generation capacity, and expected capacity use rate (*capacity factor*). In general, small-scale hydropower with a capacity of less than 10 MW has a higher LCOE than large-scale hydropower. Very small off-grid hydropower with a capacity of less than 1 MW can sometimes have a much higher LCOE than systems with a capacity between one and ten megawatts. The LCOE decreases as the expected lifetime of the generation system increases, but the effect can be relatively small due to discounting for the time value of money. The LCOE is lower for technologies with a long expected lifetime for amortization of the capital costs, such as hydropower. IPCC (2012) used a range of 40-80 years as the expected lifetime of hydropower, with a base case of 60 years.

A high discount rate favors investments with low capital costs and high operation and maintenance costs. Similarly, a low discount rate favors investments with high capital costs and low operation and maintenance costs. IPCC (2012) used a discount rate of 7 percent in its base case calculations of LCOE, but also analyzed the effects of using discount rates of three and 10 percent. In comparing LCOE estimates from other sources, check the discount rates used. The IPCC LCOE estimates were similar for the 40, 60, and 80 year expected lifetimes because of the effects of the discount rate on the present value of costs. At a 7 percent discount rate, the present value of $1.00 in year 40 is $0.07, in year 60 it is $0.02, and in year 80 it is zero. These present values would be higher at a 3 percent discount rate and lower at a 10 percent discount rate. The 12 percent discount rate used by USAID and the World Bank results in higher LCOEs for hydropower and other sources of electricity than estimates based on lower discount rates.

The LCOE decreases as the projected capacity factor increases. Actual capacity factors vary considerably by country, specific sites, and the age of the system. The IPCC (2012) analyzed IEA data and calculated a weighted world average of 44 percent for existing hydropower systems in 2009. There

was considerable regional and country variation in the data (32 percent in Australasia/Oceania, 35 percent in Europe, 43 percent in Asia, 47 percent in Africa and North America, and 54 percent in Latin America). The capacity factors for existing systems ranged from 37 percent in the United States to 41 percent in India, 42 percent in China, 43 percent in Russia, 49 percent in Norway, and 56 percent in Brazil and Canada.

IPCC (2012) assumed a 45 percent capacity factor in its generic analysis of the LCOE for hydropower. The capacity factor can increase over time, but hydropower is a mature technology with relatively low potential for technological improvements. It can also decrease over time if competing technologies become cheaper and more efficient or are considered environmentally preferable. The capacity factor for hydropower can be much lower than anticipated in years with droughts or other extreme weather, structural problems, or major maintenance and replacement.

The LCOE for hydropower varies by type of system, size, and location. Different definitions of large and small hydropower are in common use and should be taken into account in comparing estimates of the LCOE of small vs. large hydropower. The World Energy Council defined large hydropower as installations with a capacity of over 10 MW. IPCC (2012) noted that definitions of small hydropower ranged from a maximum of 1.5 MW in Sweden to 5-100 MW in the United States, 10 MW in Norway, 20 MW in Brazil and the European Union, 25 MW in India, and 50 MW in Canada and China. Electromechanical equipment costs are often the largest share of total costs in small-scale hydropower below 5 MW. The costs of civil structures tend to dominate in large-scale hydropower (IPCC 2012). Since LCOE can be estimated with or without subsidies or tax incentives, it is important to examine the assumptions before transferring the findings to other national or subnational contexts.

IPCC (2012) reported that the capital costs of hydropower commonly varied from less than $500/KW to over $5,000/KW in 2005 U.S. dollars (this would be 128.7 percent higher in 2018 U.S. dollars, reflecting inflation measured by the consumer price index (IMF 2018)). In United States, the actual cost of constructing a hydropower plant on existing conduits, non-powered dams, or along undeveloped streams ranged from $1,000-$9,000/KW in 2014 U.S. dollars. The average cost was $4,460/KW for a canal/conduit installation, $3,960/KW for a non-powered dam, and $4,800/W along undeveloped stream stretches. Unit capital costs tended to decrease as the hydraulic head increased. Only the canal/conduit systems had economies of scale with higher installed capacity.

Between 1980 and 2015, construction costs for hydropower plants in the United States were constant, after adjustment for inflation adjusted basis. The unsubsidized LCOE of recent hydropower plants ranged from $30-220/MWh, with a median of $125/MWh (O'Connor et al. 2015).

IPCC (2012) estimated how the capital cost per KW of capacity translates into LCOE, based on assumptions about the discount rate, operating and maintenance costs, capacity factor, and the expected lifetime. It assumed that annual operation and maintenance costs would be 2.5 percent of the capital costs. This is a common, but crude assumption in hydropower cost analyses. The IPCC (2012) analysis found that a capital cost of $3,000/KW yields an LCOE of $0.097/kilowatt-hour (KWh) at a 10 percent discount rate, 2.5 percent operating and maintenance cost ratio, 45 percent capacity factor, and a 40-year expected lifetime. The LCOE would be only slightly lower, $0.095/KWh if the expected lifetime were 80 years. With a 40-year lifetime and a 7 percent discount rate, the LCOE would be $0.076/KWh. If the capital cost were $1,000/KWh, the LCOE would be $0.032/KWh at a ten percent discount rate and 40 year expected lifetime. These LCOE estimates in 2005 U.S. dollars would also be 128.7 percent higher in 2018 U.S. dollars.

Pumped storage often has a higher LCOE than other forms of hydropower because of the low capacity factor, often 10-20 percent. For example, new pumped storage in Australia had an LCOE that ranged from $135-$583/MWh in 2018 (Giannoakopoulou and Brandily 2018). However, the value of pumped storage can also be relatively high since it can reduce the need for additional capital investment in new

power generation capacity to meet peak demand. Declining costs of battery storage may make new pumped storage dams uncompetitive. Between 2010 and 2017, lithium-ion battery pack prices decreased by 89 percent and electricity storage costs are expected to continue declining (Zindler 2018). Battery storage and smart grid technologies to improve demand management will have transformational effects in reducing the need for new power generation capacity by decreasing curtailment of renewable sources of electricity.

Location has a large effect on the costs of studies and regulatory approvals; labor; the delivered cost of steel, cement, and electromechanical equipment; and financing. Location also affects the capacity factor that can be achieved under the prevailing climate and hydrological conditions. LCOE estimates are typically reported by country. Global averages are also available for LCOE, but should be used with caution since the costs are site specific. LCOE estimates from different sources vary due to differences in the assumptions and data used.

IRENA (2018) and REN21 (2018a) reported that the global weighted average LCOE for new hydropower facilities at $ 0.05/kWh in 2017. However, the weighted average conceals the large amount of variation across regions and projects within the regions (Figure 6).

FIGURE 6. Comparison of LCOE for Renewable Energy Technologies, by Region or Country

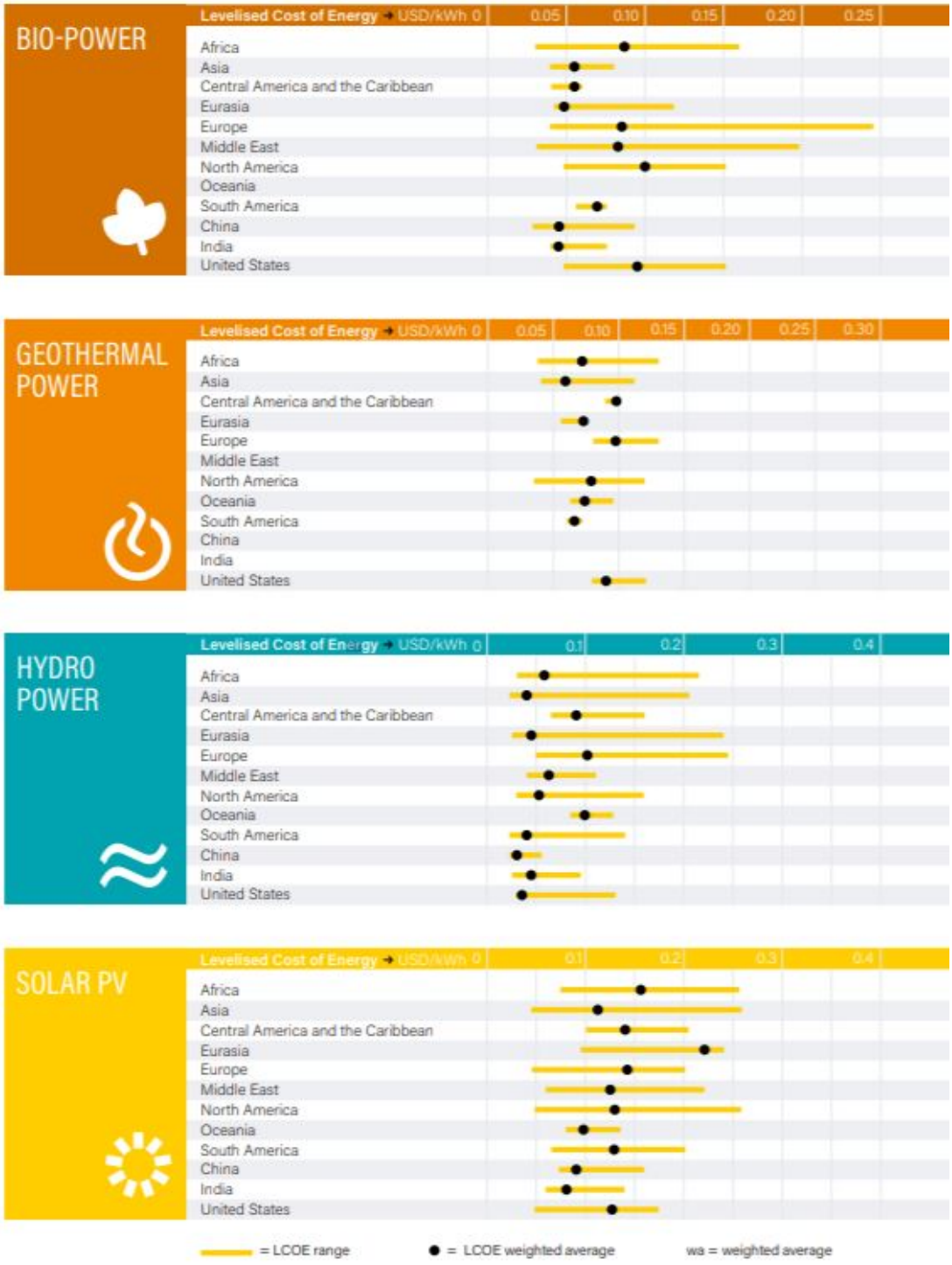
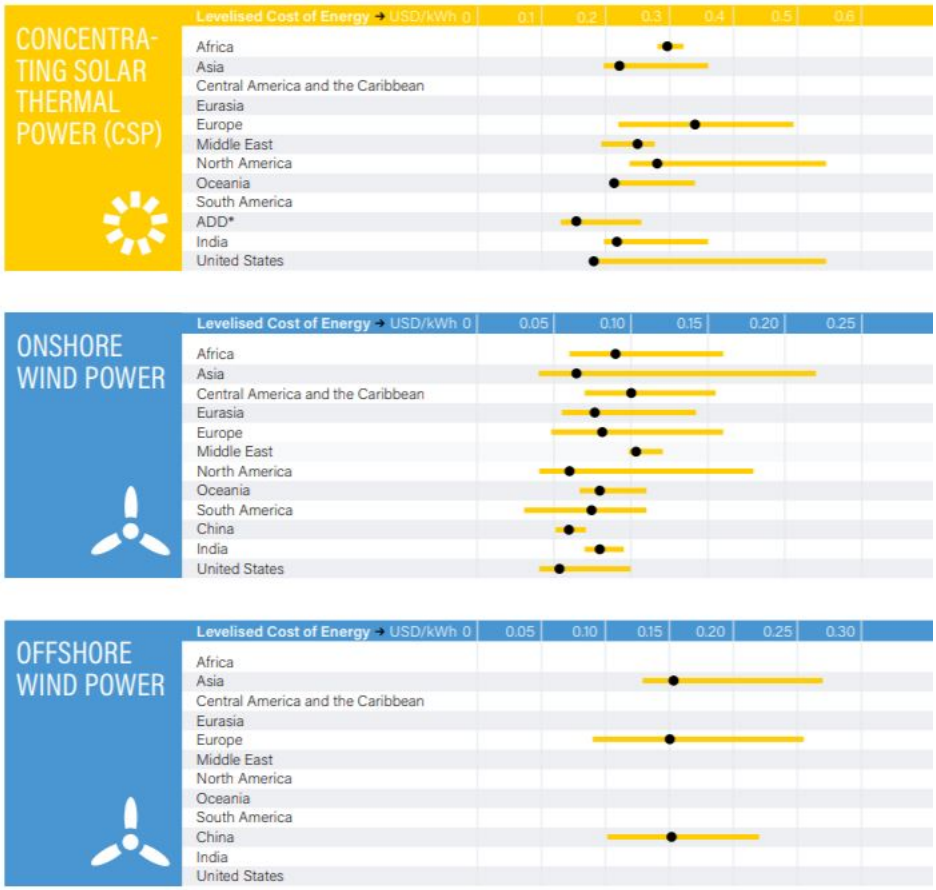


FIGURE 6. Comparison of LCOE for Renewable Energy Technologies, by Region or Country (Continued)



Source: REN21 (2017).

Since hydropower is a mature technology, the National Renewable Energy Laboratory (NREL) projected that its future capital costs through 2050 in the United States would be about the same as current costs in real terms (NREL 2018). By contrast, the capital costs of utility-scale wind and photovoltaic power have fallen sharply in recent years. The average LCOE of onshore wind power decreased 23 percent between 2010 and 2017, reaching $0.06/kWh in 2017. Auctions in 2017 commissioned onshore wind energy for $0.04 cents/kWh, equal to the cheapest competitors. The cost of utility-scale PV solar fell 75 percent between 2010 and 2017 to $0.10 /kWh LCOE of with some record low prices of $0.03 cents/KWh in 2017. New bioenergy and geothermal projects were commissioned at an average cost of $0.077 cents/KWh (IRENA 2018).

Tender bids in electricity procurements may be lower than current LCOEs since bids reflect expected future costs, especially for wind and solar technologies with declining capital costs and increasing power generation efficiencies. Also, bid terms may allow future annual adjustments in prices (REN21 2018). Table 7 contains global LCOE estimates for renewable and nonrenewable sources of electricity that compete with hydropower.

TABLE 7. Global Levelized Costs of Electricity from Non-Hydropower Sources in 2017 (U.S. Dollars/MWh)

Electricity Generation Technology	Levelized Cost of Electricity (U.S. Dollars/MWh) – Low	Levelized Cost of Electricity (U.S. Dollars/MWh) – High
Wind	30	60
Solar PV-residential	187	319
Solar PV-utility scale	43	53
Solar thermal with storage	98	181
Fuel cell	106	167
Geothermal	77	117
Biomass-direct	55	114
Nuclear	112	183
Coal	60	143
Combined cycle gas turbine	**42**	**78**

Source: Lazard (2017).

BNEF offers subscribers current LCOE estimates by technology and country that take out the effects of subsidies. It also provides LCOE forecasts for each year through 2040 to support long-term electricity planning. These estimates are updated every six months. BNEF expects that the LCOE for photovoltaics and onshore wind will continue falling and become the lowest cost sources for bulk electricity generation almost everywhere by 2023. This reflects lower production costs as well as technological improvements such as photovoltaic panel and wind turbine efficiency gains. BNEF projected that the LCOE in 2040 will be 62 percent lower for photovoltaic power and 48 percent lower for onshore wind than in 2018 (Giannakopolou and Brandily 2018).

Decisions on investment in new electric power generation capacity are also affected by other factors besides differences in the LCOE. The projected capacity use rate for new generation depends on the existing mix of power generation sources and the shape of the load (quantity demanded) over the course of a day, season, and year. To avoid outages or voltage reductions, the power grid has to continuously balance the load and supply. Some power generation technologies can vary their output to meet the load (*dispatchable technologies*). Variable or intermittent sources of renewable energy, such as hydropower and wind and solar power, are *non-dispatchable technologies*. Although hydropower systems with reservoirs provide some flexibility to respond to daily load variations, they can have high seasonal fluctuations in capacity. Non-dispatchable capacity has less value in balancing the electric grid (although this may change in the future with additional reductions in the cost of battery storage). Since the existing resource mix and capacity use rates vary across locations, the LCOE is not a sufficient measure of the economic competitiveness of different generation alternatives.

As a result, the United States Energy Information Administration (USEIA) (2018) recommended using the LCOE together with another metric—the levelized avoided cost of electricity (LACE)—to compare power generation technologies in specific locations. The LACE is the avoided cost to the electric grid, what it would have cost to generate electricity from another source in the absence of a new power generation facility. The projected avoided cost in each year is converted to a net present value.

The LACE is difficult to estimate because it depends on the marginal value of a unit of capacity in the power system's mix of generation technologies that exists now or in the future. The LACE can be compared to the LCOE to consider whether the value of a new power generation facility exceeds its cost when multiple technologies will be available to meet the load. Although both measures are simplifications of economic modeling, the combined use of the LCOE and LACE addresses more of the factors that should be considered in investment decisions than LCOE alone. Other factors that may

affect decisions include uncertainty about fuel prices and future energy and environmental policies, concerns about system reliability and diversification, and the availability of financing (USEIA 2018).

Table 7 compares the USEIA's 2018 LCOE and LACE projections for new sources of electricity entering service in the United States in 2022. Their LCOE projections reflect tax credits for renewable energy (based on the current phase-out schedule) and prevailing tax depreciation rates for all business investment. Their LCOE values are based on a 30-year time period and 4.5 percent discount rate, which are much lower than the corresponding assumptions in the IPCC (2015). However, USEIA used a higher 7.5 percent discount rate for new coal-fired and coal to liquids (CTL) generation to reflect financial risks of long-lived power plants with high carbon dioxide emissions.

There were large differences between the USEIA's LCOE and LACE estimates for some power generation technologies as a result of differences in government policies and markets. In the United States, the LACE was much lower than the LCOE due to tax credits for offshore wind, biomass, and advanced nuclear power. The LACE was much higher than the LCOE with tax credits for geothermal and photovoltaic sources and somewhat higher for on-shore wind power. However, there was little difference between the LCOE with tax credits and the LACE for hydropower or combined cycle technologies.

USEIA also found large variations in LACE for different regions and facility sizes. For example, the LACE ranged from $40.8-$74.6/MWh for hydropower, $35.9-72.1/MWh for onshore wind, $41.6-76.6/MWh for offshore wind, $36.5-$78.6/MWh for photovoltaics, and $35.8-$83.3 for solar thermal power. The unweighted average LACE for hydropower was $52.6/MWh, but the capacity-weighted average was $74.6/MWh since large-scale hydropower had a higher levelized avoided cost than small-scale hydropower.

Table 8. Difference Between LCOE and LACE for New Generation Entering Service in the United States in 2022 (U.S. Dollars/MWh)

Plant type	Average capacity-weighted[1] LCOE with tax credits	Average capacity-weighted[1] LACE	Average net difference[2]
Dispatchable technologies			
Coal with 30% CCS[3]	NB	NB	NB
Coal with 90% CCS[3]	NB	NB	NB
Conventional CC	48.3	46.5	-1.7
Advanced CC	48.1	47.5	-0.6
Advanced CC with CCS	NB	NB	NB
Advanced nuclear	90.1	43.3	-46.8
Geothermal	40.3	66.8	26.5
Biomass	102.2	45.1	-57.1
Nondispatchable technologies			
Wind, onshore	37.0	42.9	5.9
Wind, offshore	106.2	47.6	-58.6
Solar PV[4]	46.5	72.4	25.8
Solar thermal	NB	NB	NB
Hydroelectric[5]	73.9	74.6	0.7

Source: U.S. Energy Information Administration (2018).

[1] The capacity-weighted average is the average levelized cost per technology, weighted by the new capacity coming online in each region. The capacity additions for each region are based on additions in 2020–2022. Technologies for which capacity additions are not expected do not have a capacity-weighted average and are marked as *NB* or not built.
[2] The *Average net difference* represents the net economic value or the average of the LACE minus LCOE calculation, where the difference is calculated for each of the 22 regions based on the cost with tax credits for each technology, as available.
[3] Because Section 111(b) of the Clean Air Act requires conventional coal plants to be built with CCS to meet specific CO2 emission standards, two levels of CCS removal are modeled: 30%, which meets the NSPS, and 90%, which exceeds the NSPS but may be seen as a build option in some scenarios. The coal plant with 30% CCS is assumed to incur a 3 percentage-point increase to its cost of capital to represent the risk associated with higher emissions.
[4] Costs are expressed in terms of net AC power available to the grid for the installed capacity.
[5] As modeled, hydroelectric is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.
CCS=carbon capture and sequestration. CC=combined-cycle (natural gas). CT=combustion turbine. PV=photovoltaic.

Retrospective analyses have found that the actual capital costs of many hydropower installations worldwide have been substantially higher than projected. The original assumptions of the developers are often over-optimistic, especially for projects proposed for government or multilateral development bank financing. Lead times for licensing, permitting, and construction of large dams and other major infrastructure investments have often been longer than expected, increasing capital costs. In some cases, complex siting, engineering, and construction issues have emerged over time, causing major cost over-runs.

Ansar *et al*. (2014) reviewed cost records for 245 dams globally from 1934 to 2007 (186 were hydropower dams) and found that actual costs exceeded projected costs by an average of 96 percent. There were no significant differences in the size of dam cost forecasting errors over time, indicating limited learning from earlier experience. They found a nonlinear relationship between actual costs and dam height. For example, a 100-meter dam wall was typically four times the cost of a 50-meter dam wall. Dam volume increases as an exponential function of height and volume is a key factor in the costs.

Ansar *et al*. (2014) also found also a nonlinear relationship between actual costs and installed capacity. Larger systems had higher costs per unit of capacity than the smaller ones. Beyond a certain size, there may be diseconomies of scale and longer schedule overruns due to the need for customized materials and more complex construction techniques for larger unit dams. Pre-manufactured components may be available for smaller dam walls and turbines. Large hydropower facilities in developing countries may require more imported materials, increasing the potential for delays and cost overruns due to currency risks.

The average completion time for the large dams was almost nine years. The average delay was 2.3 years and there were delays in 80 percent of the large dams. New large-scale hydropower facilities cannot meet a short-term demand for electricity due to the long lead time for planning and construction. Ansar *et al*. (2014) found that each year of delay in their study sample increased cost overruns by an average of 5 to 6 percent, although this varied by country. Delays also postpone the benefits from the investment, reducing the present value of net benefits. Nearly half of all large-scale hydropower projects in India were facing delays in early 2017 (REN21 2018b).

The risk of large cost overruns is higher when inadequate information has been gathered in the planning stages and siting. A 20 percent cost contingency was budgeted for the Itumbiara hydropower facility in Brazil due to site's geology, but the actual costs of addressing the site conditions were 96 percent higher (Ansar *et al*. 2014). Although additional costs would be incurred for better studies of site conditions and changes in designs and implementation plans, the total costs are likely to be lower if this work is done before construction begins.

Sovacool, Nugent, and Gilbert (2014) analyzed 401 power plants of various types in 57 countries and approximately 75 percent had cost overruns. They found that the average cost overrun was 71 percent for hydropower 117 percent for nuclear, 13 percent for thermal, 8 percent for wind, and 1 percent for solar power. Flyvbjerg (2008) recommended better forecasting to reduce the risk of cost overruns for large dams by using actual cost data from investments of a similar size and type.

The expected life of hydropower reservoirs in developing countries has often been overestimated because the effects of sedimentation on the life were not adequately considered. As a result, benefit projections were often inflated. Sediment removal can help maintain the useful life, but it is costly and only partly effective. The World Bank now promotes a life cycle management approach that addresses sediment management and good safety and environmental practices in decommissioning dams (Annandale, Morris, and Karki 2016).

Good sediment management practices can extend the life of a reservoir, but increase operation and maintenance costs. Sediment can be diverted, removed, or controlled. A weir is typically used to divert sediment. The weir operates during high flows when sediment concentrations are high. Diversion of sediment-laden flows is most cost-effective at dams on the bend of a river. Sluicing/drawdown routing reduces reservoir water levels before high stream flows from floods arrive. Dredging it is expensive and may be needed throughout the life of the dam. Dredging six million m3 of sediment at the Loiza reservoir in Puerto Rico in 1997 cost $10 per cubic meter of sediment removed.

A reservoir can be flushed by emptying the reservoir by opening bottom outlets so that the incoming stream flows scour sediment, but it generally only removes a core of sediment along the channel. Pressure flushing can be done by partially drawing down the reservoir to move coarser upstream sediments closer to the dam, but it often does not clear fine sediments.

Erosion control is the most widely recommended sediment management technique, but is not often done because land owners and users in the watershed would have to bear additional costs and may not have sufficient incentives or knowledge to participate. Structural/mechanical measures reduce overland or channelized flow velocity and increase surface storage of sediment through terraces, conveyance

channels, check dams and sediment traps. Vegetative erosion control uses plants to retain the soil and includes reforestation, planting shrubs or grasses, and improved agricultural practices. Operational measures include scheduling construction, agricultural clearing, or timber harvesting when weather and soil conditions are less likely to cause high erosion rates (Schellenberg et al. 2017).

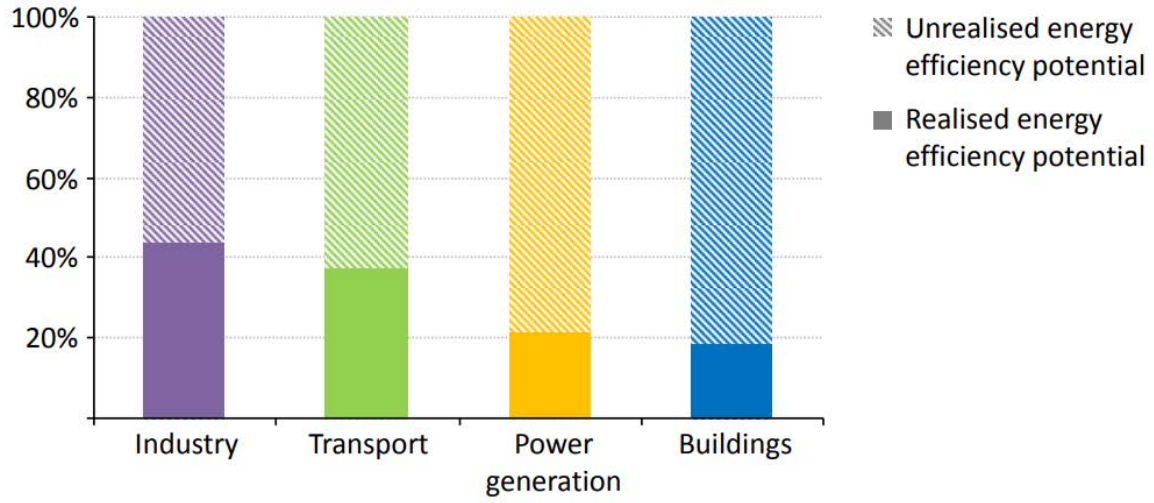
4.3 POTENTIAL FOR ENERGY EFFICIENCY TO REDUCE THE DEMAND FOR HYDROPOWER

Investments and policies to increase energy efficiency can be less costly than developing new hydropower facilities. Molina (2014) estimated that energy efficiency in the United States had an effective LCOE of $20-$45 per megawatt-hour. Investments in energy efficiency can reduce the number or size of hydropower dams needed to meet the projected demand for electricity or postpone the time when the capital investment would be needed.

Global investment in energy efficiency improvements reached $231 billion globally in 2016, up 9 percent from the previous year (IEA 2017). Energy efficiency improvements over the last 15 years have saved 3.1 billion tons of oil equivalent worldwide, approximately 36 petawatt-hours (World Energy Council 2016a).

However, the IEA (2014) estimated that two-thirds of the total global energy efficiency potential through 2035 from electricity and other energy uses could not be realized without policy and regulatory changes. Without these changes, the energy efficiency gains in buildings may be only 20 percent of the potential (Figure 7). Common barriers to energy efficiency investments include insufficient information on the costs, benefits, and reliability and sourcing of technologies; subsidies for production or consumption of energy; problems in metering, billing and collecting utility charges; and insufficient access to financing.

FIGURE 7. Energy Efficiency Potential, Realized and Unrealized, By Sector in 2035



Source: Kesicki (2015).

5. CONCLUSIONS

Based on the full range of studies available, it appears likely that hydropower reservoir dams *typically* have far lower life cycle GHG emissions than coal, petroleum, or natural gas thermal power plants and similar life cycle GHG emissions to nuclear, photovoltaics, and wind power systems. However, there is still tremendous uncertainty about the direct and indirect GHG emissions from hydropower, and there are some notable examples of hydropower systems that have emissions as high or higher than fossil fuel powered thermal power plants, suggesting that significant care needs to be exercised in the location and design of hydropower dams to ensure lower life cycle GHG emissions.

The risks of high GHG emissions from hydropower reservoirs can be reduced by:

- Ensuring a high power density, preferably greater than 1 W/m^2 of reservoir surface area;
- Minimizing the inundated area and removing terrestrial biomass before inundation;
- Siting nutrient sources upstream from reservoirs and implementing nutrient reduction strategies;
- Incorporating design features, equipment, and operating measures to reduce CH_4 emissions from degassing of turbines and emissions downstream of the impoundment (including drawing water for the turbines close to the reservoir surface); and
- Re-engineering old reservoirs to increase power production, for example, through sediment removal;
- Decommissioning reservoirs with declining power output that cannot be improved.

Other environmental impacts of hydropower systems are significant and include alteration of flow regimes, changes in water quality, lower fish populations and fish diversity, and flooding of habitat that reduces terrestrial biodiversity. Hydropower systems can also have significant social impacts, including displacement of people during dam establishment, with particularly harmful effects on indigenous groups, marginalized populations, and women. Displacement can lead to unemployment and underemployment, loss of access to key resources, reduced income from farming, disruption of social and community networks, and public health risks. Adequate compensation in cash or in kind has rarely been offered to people displaced by hydropower development. Furthermore, protocols, assessment tools, and standards that have been developed to mitigate the negative environmental and social impacts of large-scale hydropower have not been widely used and are not broadly acceptable to key stakeholders.

New hydroelectric power investments can support national and subnational economic development and energy self-sufficiency or exports. Increased employment from large dam construction can continue for a decade or longer. Hydropower dams can also increase economic production from irrigated agriculture, aquaculture, and reservoir-based fisheries for greater food security and rural poverty reduction. Reservoir dams can manage a river's flow, capture heavy rainfall to mitigate drought, and reduce flooding. They can also provide water for irrigation and human and animal consumption.

However, the actual financial and economic viability of large-scale hydropower has often been below projections. The economic costs of hydropower have often been underestimated or reduced by subsidies and the economic benefits have often been overestimated. In addition, the environmental and social costs have generally not been valued at all. In addition, lengthy delays in completion are common and increase cost over-runs.

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