ENVIRONMENTAL EFFECTS OF HYDROPOWER PLANTS INCLUDING THOSE USING THERMAL, TIDAL AND WAVE POWER

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Summary

This article presents a discussion on the technical aspects of four forms of hydropower—riverine, tidal, wave, and ocean thermal. Each discussion begins by describing the process by which solar (or, in the case of tidal hydropower, gravitational) energy is transformed into electricity, and presents (where available) estimates of the availability of useable energy from each form. This is followed by a discussion of the history of the use of each form of hydropower and a basic description of the technology used for transforming hydropower into electric power. A summary of the range of environmental, social, and economic factors for each form of hydropower follows.

The article follows with a speculative discussion on why and how conventional hydropower technologies have proliferated, leading to their associated social and environmental consequences. While electric demand is identified as a major factor, other technical (e.g. reliability, load factor), economic (e.g. profitability), political (e.g. decision-making processes, vested economic, bureaucratic and political interests, public participation), and social (e.g. media portrayal of hydropower development, ecological and social norms) factors are also important to consider. Changes in each of these factors can give rise to changes in choices of technology, and the article considers what types of technology choices may follow from the evolution of these other factors.

1. Introduction

A chapter discussing the environmental impacts of hydroelectric power should move beyond the electric power sector and investigate the many roles that hydropower has been called upon to play in human society. For example, major dams have been colossal public works, often built with the promise not just of generating electricity but also of providing flood control, navigation, water for irrigation and drinking, and a number of other benefits. In many cases, the generation of electricity has been a secondary consideration in the construction of the dam and in its operating pattern.

The development of hydroelectric power, however, has not been driven solely by concern for human progress and quality of life. The construction of huge dams has frequently been used to advance nationalist or ideological agendas. Their roles, as massively visible symbols of "progress," have often been more important in ensuring dam construction than utilitarian cost-benefit issues. Of the many forms of electricity generation in use by the human race, none rival hydroelectric power in their presence on the landscape. The proposed Three Gorges Dam on the Yangtze River in China is projected to require the displacement of between 1.2 and 1.8 million people from their homes and homeland. Archaeologists estimate that nearly 8000 unexcavated archaeological sites will be lost forever below the reservoir to be created in the construction. Such an undertaking recalls the ancient wonders of the world in its magnitude, and the political prestige and engineering pride associated with building such a mega-monument has certainly influenced the commitment to construct the

18 200 megawatt (MW) dam, the largest public works undertaking in China since the construction of the Great Wall.

It is only recently that environmental concerns have played a major role in decisions to develop hydropower resources. The increasing scarcity of areas untrammeled by industrial development, an increased awareness of the impacts of dams on ecosystems, and the increased political power of organizations that support environmental causes have all contributed to this change. After forty years of heady dam construction in the United States, the US Supreme Court in 1978 upheld an injunction against the construction of the Tellico Dam on the basis of the Endangered Species Act. Dam construction has also encountered resistance from the local people negatively affected by dams and increasingly over the past decade from their supporters in human rights groups at both national and international levels. This is particularly true in developing countries where large dams have required the forced displacement of tens of millions of people. Many more have been negatively impacted because their livelihood depends upon the unimpeded flow of water, nutrients, sediments, and aquatic organisms up and down a river or through an estuary.

This article attempts to present a discussion on the technical aspects of hydropower development within the social and political context described in this introduction. It is divided into four sections, covering riverine, tidal, wave, and ocean thermal hydroelectricity sources. Each section describes the hydrologic and meteorological processes that make energy available in those forms, presents a discussion on the technologies that are utilized to harness electricity from those energy sources, and categorizes the range of potential environmental impacts associated with each practice. Each section concludes by also addressing the potential social and economic consequences associated with each range of technologies. The article concludes by discussing technical, economic, political, and social dimensions of hydropower use, and how changes in society along those dimensions may affect the future use of hydropower and its associated environmental impacts.

2. Riverine Hydropower

Hydropower is often considered “renewable” because of its dependence on the solar-driven hydrological cycle of rainfall and evaporation. However, while the resource exploited by hydropower is renewable, the technology itself is in many cases non-renewable as reservoirs gradually lose their water storage capacity to sediments carried from upstream and because the number of viable dam sites is finite. Hydropower can therefore only be considered a true renewable if the potentially mammoth costs of refurbishing or replacing obsolete dams and disposing of the sediments, which have accreted behind them is taken into account. While removing sediments may be economically and technically feasible for some smaller projects, there are as yet no indications that it will be for the great majority of the very large reservoirs built in the past 60 years. Some methods such as reservoir flushing can be used to prevent sediments accreting in reservoirs to significantly damaging levels. However these hamper reservoir performance and only work in specific hydrological and topographical circumstances.

The hydrologic cycle is driven by the solar flux—energy amounting to about 750 watts per square meter (W/m2) falling on the earth's surface waters. As solar energy falls upon bodies of water, water molecules evaporate and are carried by convection into the atmosphere. These water molecules coalesce into clouds and are carried by winds inland. When rain falls on upland areas, the hydrologic cycle has imparted an amount of potential energy to the water equal to the weight of water transported multiplied by the increase in height (the difference between sea level and the land elevation where the rain has fallen). This potential energy is expended as water flows across land into streams and rivers to return to freshwater lakes or the seas or oceans.

The potential amount of energy available for riverine hydropower varies with topography and climate. The greater the change in elevation, the greater the potential energy associated with hydropower—hence, more mountainous regions have a greater potential energy availability. Also, the amount of precipitation varies across each continent. Wet, mountainous regions with heavy rainfall or a seasonal snowpack will be a greater source of riverine hydropower than dry, mountainous regions, or regions with a perpetual snowpack. However, while large quantities of potential energy may be available in certain areas, site characteristics such as slope, soil, and rock formations, and distance to electric demand areas determine whether this energy is technically usable.

Table 1 presents the estimated theoretical and technical potential energy available (expressed in terawatt-hours, or TWh) on each continent from riverine hydropower. Japan, the USA and Canada have each exploited around 70 percent of their estimated "economically feasible" hydropower potential; Europe about half of its potential; while Africa, China and Latin America have developed only around one-tenth of theirs. Estimates of unexploited potential must, however, be interpreted with caution, not least because of the paucity of reliable hydrological data for most of the world's rivers. Hydropower potential data also take no account of geological constraints or the social and environmental impacts of the dams needed to tap unexploited potential. Furthermore, the criteria used to define "economically feasible" are vague and vary between countries.

Region	**Theoretical potential (TWh)**	**Technical potential (TWh)**
Africa	10,118	3,140
North America	6,150	3,120
Latin America	5,670	3,780
Asia (excluding former USSR)	16,486	5,340
Australasia	1,500	390
Europe	4,360	1,430
Former USSR	3,940	2,190
World	**44,280**	**19,390**

Source: [4]

Table 1. Theoretical and technical potential hydropower availability

This section investigates the history and technology associated with riverine hydropower development, classifies and describes the range of energy-environment interactions, and discusses a range of other aspects of riverine hydropower development.

2.1. History and Technology

Humanity has been utilizing hydropower for millennia. The flow of rivers and streams was used in ancient times to power water wheels. The rotation motion of the wheel could rotate millstones to grind wheat and other grains into flour or meal, or lift water out of a river for use in irrigation. By the time of the Roman Empire, advanced designs would confine water to a channel and guide it over the water wheel rather than under it, increasing the efficiency of the transfer of water current to mechanical output. The largest complex in this time period had a power output of about 15 kilowatts (kW). The ability to utilize hydropower increased greatly with the invention of the hydraulic turbine in 1849. The first hydroelectricity plants were built in the United States and Norway in the 1880s.

According to the estimates of the International Commission on Large Dams (ICOLD), the leading dam industry association, there are around 45 000 large dams in existence, all but 5000 of them built since 1950. ICOLD defines a large dam as one 15 meters or more from foundation to crest, although lower dams may also meet ICOLD's large dam criteria depending on other parameters such as spillway capacity (the potential flow rate through the water level regulator) or crest length. Only a minority of these 45 000 dams are used for hydropower production. The proportion varies regionally between around 6 percent of dams in Africa having a hydropower component to around 33 percent of dams in Europe. More than 300 dams worldwide are defined as "major," meaning they meet one or more of the following criteria: a height of at least 150 meters; a volume of at least 15 million cubic meters, reservoir storage capacity at least 25 cubic kilometers; electrical generation capacity at least 1000 megawatts. These major dams account for about 40 percent of existing hydroelectricity production.

Around 18 percent of the world's electricity and six percent of primary energy supply is provided by hydropower. The proportion of each continent's electricity generated by hydropower varies from around 15 percent in Asia to almost 60 percent in South and Central America. Fifty-one countries are dependent on hydropower for more than 70 percent of their electricity, two countries (Norway and Iceland) in the "First World" and 49 countries in the "Third World" and the former Communist bloc.

Dams have two basic functions. The first is to store water to compensate for seasonal or annual fluctuations in river flow or in demand for water and energy. The second is to raise the level of the water upstream to enable water to be diverted into a canal or to increase "hydraulic head"—the difference in height between the surface of a reservoir and the river downstream. Reservoir volume is usually controlled by means of a "spillway" which allows excess water to flow past the dam (this also provides a release valve in the event of floods).

Hydropower generation capacity is a function of the amount of flow and hydraulic head. Although the head is usually related to the height of the dam, a low dam can have a high head if the powerhouse with its turbines and generators is located some distance downstream of the dam. Pipes, known as "penstocks" direct water from the reservoir to the turbines. Once the water has spun a turbine it flows into the "tailwater" below the dam through a "tailrace" pipe. (In some cases a high head may be exploited by discharging reservoir water through tunnels and channels to a powerhouse on another nearby river at a lower elevation.)

There are two main types of hydropower plant operating patterns—"storage" and "run-of-river." Storage plants have reservoirs, which allow them to store water from wet periods so that they can generate power during seasons or even years of low rainfall. Plants with large reservoirs are generally used for generating a relatively steady output of "baseload" power year-round. Even the largest reservoirs, however, are vulnerable to prolonged droughts, which can reduce their power generating ability.

A reservoir also allows a hydropower plant to store water during times of low power demand and then quickly to start generating (or step up generation) during the peak hours of electricity use. Hydropower's suitability for generating valuable "peaking" power has in recent years encouraged a boom in what are known as pumped-storage plants. These involve two, normally relatively small, reservoirs, one above the other. During peak hours, the water from the upper reservoir falls through turbines into the lower one, generating electricity. The water is then pumped back uphill again using less expensive "off-peak" electricity.

Run-of-river dams raise the water level upstream but create only a small reservoir ("head pond") and do not have enough storage capacity to effectively regulate downstream flows. The electricity generation of a run-of-river hydropower dam is proportional to the flow of the river at any given time. Run-of-river projects tend to have fewer environmental impacts than storage dams although their impacts, particularly on migratory fisheries, can still be significant. Furthermore, there is no clear distinction between a run-of-river project with a large head pond (relative to the magnitude of river flow) and a storage dam with a small reservoir.

2.2. Energy and Environment Interactions

By disrupting the volume and timing of the flow of water, sediments and nutrients downstream, and by converting riverine and terrestrial habitats to lacustrine (lake) habitats, hydropower dams can have tremendous local and regional environmental impacts. As is shown in Table 2, these impacts result from both the existence of the dam as well as the operation of the dam. Swedish researchers estimate that 60 percent of the length of the world's large river systems are highly or moderately fragmented by dams, inter-basin transfers and water withdrawals for irrigation."

Impacts Due to Dam and Reservoir Existence	**Impacts Due to Pattern of Dam Operation**

Upstream change from river valley to reservoir	Changes in downstream hydrology: (a) changes in total flows (b) change in seasonal timing of flows (c) short-term fluctuation in flows (d) change in extreme high and low flows
Changes in downstream morphology of riverbed and banks, delta, estuary and coastline due to altered sediment load	Changes in downstream morphology cause by altered flow patterns
Changes in downstream water quality: effects on river temperature, nutrient load, turbidity, dissolved bases, concentration of heavy metals and minerals	Changes in downstream water quality caused by altered flow patterns
Reduction of biodiversity due to the blocking of movement of organisms and because of the above changes	Reduction in riverine/riparian/floodplain habitat diversity, especially because of elimination of floods

Source: [9]

Table 2. Summaries of environmental impacts from riverine hydropower

To provide more specific information on these environmental impacts, the discussion has been organized according to hydrological impacts, water chemistry impacts, sedimentological and morphological impacts, and habitat fragmentation impacts.

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Biographical Sketches

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