Hydropower

An Overview of Critical Factors for Energy Resources

Introduction

America generates energy from a number of sources. At its most basic level, each source turns a turbine to generate electricity. That power is then fed into the electrical grid to be distributed to homes and businesses. America consumes 4 trillion kilowatt hours (kWh) of electricity per year. The energy mix to generate this electricity is a blend of public policy and private action. Hydropower was used to generate 7.3 percent of America's electricity in 2020.

This policy brief will outline eight key factors that shape the current and future utilization of hydropower for American energy needs. To help build a comprehensive picture of hydropower's energy outlook, this brief will examine its energy density, costs to generate energy, availability and reserves, land needed, overall safety record, climate impact, long-term impact, and potential limitations of the energy source.

Basics of Hydropower

Hydropower collects energy from the natural flow of water in rivers, waterfalls, and other bodies of water that possess strong enough currents. Water has been utilized as a source of kinetic energy for millennia, with ancient civilizations even using water to power small-scale grain processing. Today, hydropower has the capability to be a major energy source for both inland and coastal areas.

Hydropower can take several different forms, but the process of harnessing the energy is largely the same. Water possesses potential energy when it is about to spill over a high point or travel downhill.[1] Hydroelectric energy plants harness the kinetic energy as water flows downhill by using the water to rotate turbines, which in turn generate electricity.[2]

The three different types of hydroelectric energy generation are impoundment, diversion, and pumped-storage facilities. Impoundment facilities usually are large dams that store river water in a reservoir, which is released to flow through a series of turbines that activate generators, producing electricity.[3] A diversion facility channels a river or other large body of water through a penstock or a diversionary channel, where it collides with turbines, producing energy. Pumped-storage facilities are a form of energy storage for other sources of energy for future use. By pumping water uphill to a high elevation, it stores energy for times where energy demand is high.[4] When released from this higher elevation, large amounts of energy can be generated.

1. Energy Density

The energy density for hydropower depends on several factors, including properties of water, spatial factors, and engineering constraints. Water possesses great potential energy due to its weight and density relative to air or steam used for other power generation.[5] The potential energy of stored water at a given height, or flowing water, help determine the electrical power that can be generated by rushing through a turbine. The power available to a turbine can be generally determined by multiplying the efficiency of the turbine, density of water, gravitational acceleration, height water is above the surface, and flow rate and velocity.[6,7] For example, one liter of water per second when dropped from a height of 90 meters on a turbine generates 0.72 kW of power.[8] Determining actual electricity means multiplying the max output (kW) by annual hours by the plants capacity factor, because not all plants operate consistently or continuously.[9]

In 2020, over 1,400 U.S. hydroelectric facilities, operating at around 40 percent capacity,[10] produced a total of 281 billion kWh of electricity.[11] This would equate to around 193 million kWh per plant in that year.[12]

To picture the energy density of hydropower, consider how many plants it would take to power a modern house. The average U.S. household consumes 10,649 kWh of electricity per year.[13] To run the average household for one year using the national average for conventional hydroelectric plants, it would take 0.000055 of a power plant (or a single 3.3kW plant). Adjustments to flow rates, efficiency, and others can determine how much water a single house would need.[14]

2. Cost

With no fuel costs and a long lifespan, hydroelectric power is efficient and low-cost. In 2019, the average cost of electricity from hydropower in North America was 8 cents/kWh.[15] Hydroelectric power has seen falling prices across the past two decades, with prices projected to continue downward. Overall, hydropower is capable of capturing up to 90 percent of the kinetic energy from flowing water, making it highly energy efficient.[16] Additionally, hydroelectric plants have longer lifespans than other energy infrastructure, averaging around a century.[17]

Economies of scale play a large role in the cost effectiveness of hydropower, with larger dams and hydroelectric facilities with multiple turbines being highly cost-effective.[18] Small-scale hydroelectric dams and similar projects are not always economically viable, as the small amount of energy produced could take decades to pay off the costs of the construction and installation of turbines and generators.[19] Micro-hydropower is a growing industry, although costs vary widely.

Factoring in capital costs, fixed operations and maintenance (O&M) costs, variable costs that include O&M and fuel costs, financing costs, an assumed utilization rate for each plant type, and waste management and storage, the total cost comes in higher. Accordingly, the leveled cost of electricity and storage outlook for hydroelectric power is projected to be 5.53 cents per kWh.[20,21] It would cost $588.89 total to power a U.S. household solely on hydropower for one year.

3. Availability and Reserves

The availability of hydropower depends on having an adequate amount of water to utilize for power. This makes rivers and reservoirs ideal for power generation, with coastal regions able to utilize tides as well. In the United States, the Pacific Northwest, as well as the areas surrounding the Appalachian and Rocky Mountains make up a large percentage of U.S. hydropower generation.[22] Hydropower is possible wherever water is stored at altitude, runs down a slope, or flows consistently.[23] In areas where hydropower is feasible, the water available should be infinite as long as no upstream barriers are introduced.

The U.S. over 3 million miles of major rivers, lesser waterways, canals, lakes, dams, and more.[24,25] While the U.S. generates only around seven percent of its energy from hydropower, only a fraction of its existing dams are equipped with hydroelectric turbines to produce energy. An estimated 12 million kW potential capacity lies in regular non-power dams.[26] Tapping into this could generate 45 billion kWh of electricity in addition to the capacity currently online.[27]

Considering that dams and reservoirs hold back trillions of gallons of water and its potential energy, they function as resources reserves for hydropower. Water can be released as needed to generate a specific amount of electricity. The total U.S. installed capacity of 80 gigawatts in conventional hydroelectric has the ability to produce 645 billion kWh at full capacity.

4. Land Required

Unique among other energy sources, hydropower's total footprint is almost entirely made up by and constructed over water. This still implicates land-use, as dams can create artificial lakes and reservoirs usurping land, and service roads, power lines, and other supporting infrastructure are needed to generate hydroelectric power.

Due to the multiple different sizes and topographies of states that utilize hydroelectric power, the amount of land required for a functioning hydroelectric facility varies widely. U.S. hydropower is concentrated in the Pacific Northwest, but is found in 48 states.[28] The greatest spatial area occupied by hydropower are the large reservoirs that form behind the dam.[29] Relative to bodies of water themselves, dam infrastructure and facilities on existing rivers or diversion channels take up the least amount of acreage for hydroelectricity. The footprint is determined by total land occupied by infrastructure, water, and supporting featured, but is contextualized by dividing with total energy output.

As of 2019, there were 1,452 conventional hydroelectric plants (and 40 pumped storage plants). Currently, hydropower takes up 8.7 million acres in the U.S[30] and generates 291 billion kWh, equating to a land intensity of around 33,448.28 kWh/acre.

In order to power a single average U.S. household for a year with hydropower, 0.32 acres (1,295 square meters) would be needed.

5. Safety

Hydropower has one of the lowest fatality rates of any energy source, as little or no mining or dangerous resources extraction is needed, and no pollution is generated by hydroelectric plant operation. Hydropower is estimated to have a worldwide average of 0.02 fatalities per terawatt hour (1 billion kWh) since 1990.[31] Most safety risks come from the initial construction process, where large amounts of water and concrete need to be moved and put into place. However, rare dam collapses and floods can lead to enormous loss of life, as with the Chinese-Soviet dam collaboration in the 1950s.[32] Accounting for this catastrophe and others stretching back over 70 years, the fatality rate for hydroelectric power rises to 0.1 to 0.16 deaths per billion kWh.

The risks associated with dam failures or collapses today are largely constrained to smaller embankment dams.[33] Needless to say, the global statistics are inflated by China and Soviet-era technology and practices, and are not representative of American engineering and regulatory oversight. Most dam failures that do occur in the U.S. are the result of under-maintained and older dams built during the mid-twentieth century.[34] In fact, only 3.8 percent of U.S. dam failures in the last 170 years have led to any fatalities, and hydropower dams only account for three percent of total dams in the United States.[35]

Using global data from 1990 to the present, the fatality rate to power an average U.S. home for a single year would be 0.0000002 human casualties. This would mean that 5 million homes could be powered before a death was attributable to hydropower.

6. Climate Impact

Hydropower does not generate direct emissions from its operation, nor from damming water or river diversion. However, manufacturing of inputs and construction of plants do produce direct carbon dioxide and other emissions on the front end. The median carbon emissions from hydropower energy production on a lifecycle basis is estimated at 24g CO_2/kWh of electricity.[36]

Broader environmental risks of hydroelectric dams are usually associated with fish health, water quality, and algae growths in the reservoir. Currently in the U.S., hydropower plants are responsible for killing 10 to 15 percent of fish drawn through turbines, with the best available killing 5 percent.[37,38] Fish-ladders, in-take screens, and an assortment of other technologies exist to allow migratory fish, amphibians, and other wildlife dependent on the river to move freely upstream and downstream. Incorporation of these technologies into dams have mitigated dams impact on river life.[39] Reservoirs will have larger amounts of sediments and nutrients, which increases the amount of algae and aquatic weed growth that can crowd out wildlife and other native species, necessitating their harvesting and continued management.[40] Further, studies have shown that reservoirs with large amounts of plant and algal growths can emit huge amounts of potent methane alongside carbon dioxide.[41] Emissions from reservoirs vary widely depending on the region and surrounding landscape, yet proper maintenance and harvesting of aquatic plants and keeping algal growths under control minimize this risk of natural methane emission.[42,43]

While reservoirs present a balance of photosynthesis capturing emissions and decomposition releasing methane, the exact climate impact is difficult to settle. Globally, some hydropower reservoirs are believed to be net emitters on par with fossil fuels.[44]

Based on the median lifecycle emissions to build and operate a hydroelectric facility, emissions generated to power a single American household would total 2,981.72 pounds of carbon dioxide per year.

7. Long-Term Impact

The three concerns arising from use of hydroelectric power relate to damming, and are therefore also long-term impacts of reservoir and river infrastructure more broadly, not only hydroelectric specifically. These include impacts to migratory fish and other wildlife, land use, and greenhouse gas emissions.[45]

One of the largest and most impactful factors of hydroelectric power is the death of fish passing through turbines and the long-term change of migratory patterns.[46] Fish and other aquatic life may be able to utilize fish-ladders and in-take screens to bypass the large turbines, but the volume of fish that need to get through the dam and the amount of available space can restrict the number of fish that can migrate downstream.[47] To account for this environmental impact some facilities have constructed alternative ways for fish to get through the dam, with smaller dams utilizing smaller amounts of water.[48]

Constructing dams can result in the moving of people and animals, alongside the covering of agricultural land, archaeological sites, and previously economically productive land.[49] Diverting rivers, damming water, or flooding areas to create a reservoir can change the nature of ecosystems. Environments will adapt to these changes and adjusted fish migrations, however reliant river traffic or aquaculture may spell economic consequences as well.

Hydropower does not generate significant carbon dioxide emissions from its operation, but dams and reservoirs can create the conditions for natural emissions. With the potential for biological growth, death, and decay occurring within reservoirs, unmaintained areas may lead to methane emissions. While this is natural, methane is far more potent as a greenhouse gas than carbon dioxide, and these emissions are avoidable through maintenance.

8. Limitations

The single biggest limitation of hydropower is it does need at a minimum, a river or large body of water to produce energy. Unlike other power plants, which can be built virtually anywhere across the country, hydropower can only practically be built on or near significant water resources. Technology being developed for more accessible forms of offshore hydropower may give coastal states the ability to harness energy from the changing tides, but that technology is still in development for scaleability.[50]

Due to hydropower's currently restrictive requirements, many states have constructed either artificial lakes or micro hydropower facilities to supplement other forms of energy production. The multiple different systems that micro-hydropower provides have the potential to make up a larger percentage of small-scale power production.[51]

A final limitation can be related to permitting and licensing.[52] The impacts and footprint of hydropower means that significant environmental study and quality standards must be met before a planned hydroelectric facility can be built. This can be a multiyear process, during which economic, political, and even environmental conditions can change.

Conclusion

The U.S. has utilized hydropower for decades and implemented dams across thousands of the nations waterways. As political trends move toward lower-emission energy sources, reconstituting many of the non-powered dams may be on the horizon. Overall, hydropower is relatively energy dense so long as a strong flow of water is maintained. It is low cost and utilizes freely available resources with no fuel costs. While the total footprint of hydropower is large, much of the acreage comprises river, lakes, and reservoirs. The safety record of hydropower is impressive, and while it emits no carbon dioxide during operation, reservoirs can create the conditions for natural methane emissions if not well maintained.

These factors position hydropower to be a unique form of energy for the United States, with great capacity to be tapped when needed. With the advent of new innovative micro-hydropower and the potential to capture energy from tidal activity, hydropower could soon account for as much as half of the electricity generated along certain coastlines. Advancements in technology will not only open the door to greater efficiency of existing facilities and bring new capacity online, but could help mitigate environmental impacts as well. With solutions for impact to fish, regional environments, and local communities, the benefits of hydropower could establish it as the foundation of the renewable energy portfolio, providing electricity on demand to some regions by releasing water when solar, wind, and other forms of energy are intermittent.

Citations and Notes

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