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U.S. DEPARTMENT OF
ENERGY

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Hydropower Technology

Chapter 4: Technology Assessments

Introduction

Hydropower has provided reliable and flexible base and peaking power generation in the United States for more than a century, contributing on average 10.5% of cumulative U.S. power sector net generation over the past six and one-half decades (1949–2013).[1] It is the nation's largest source of renewable electricity, with 79 GW of generating assets and 22 GW of pumped-storage assets in service, with hydropower providing half of all U.S. renewable power-sector generation (50% in 2014).[2] In addition to this capacity, the U.S. Department of Energy (DOE) has identified greater than 80 GW of new hydropower resource potential: at least 5 GW from rehabilitation and expansion of existing generating assets,[3] up to 12 GW of potential at existing dams without power facilities,[4] and over 60 GW of potential low-impact new development (LIND) in undeveloped stream reaches.[5] However, despite this growth potential, hydropower capacity and production growth have stalled in recent years, with existing assets even experiencing decreases in capacity and production from lack of sustaining investments in infrastructure and increasing constraints on water use.

Market Application

National opportunities for hydropower technology deployment exist in three major resource classes: existing water infrastructure (including non-powered dams [NPDs] and conduits), LIND in undeveloped streams, and pumped-storage hydropower (PSH). In addition to clean power generation, hydropower provides many strategically valuable ancillary benefits that are uniquely suited to support further integration of other variable renewable energy technologies.

Existing Water Infrastructure

Opportunities exist to improve performance and increase generation at existing hydropower facilities and to add hydropower to NPDs and conduits. At existing hydropower facilities, near-term improvements are possible through upgrades to make aging hydropower units more efficient, more flexible, more fish-friendly, and capable of aeration to improve water quality. Some facilities have sufficient peak flows and energy market pricing to economically justify the installation of larger, more efficient, or additional units. Still other facilities typically have environmental minimum flow requirements and energy market pricing that justify the addition of a small auxiliary unit to pass minimum flows more efficiently than large units.

Existing NPDs also present opportunities to develop hydropower without incurring the costs and impacts of additional dam construction and operation and with minimum environmental impact (e.g., no new impoundment). As noted above, up to 12 GW of potential exists at NPDs, which were built for purposes such as navigation, water supply, irrigation, and flood control but could easily accommodate hydropower development without major disruption of these other obligations. The U.S. Army Corps of Engineers, which owns and operates the largest of these facilities (locks and dams on large navigable rivers), does not have the statutory authority to construct new hydropower. As evidenced by the number of preliminary permits issued by the Federal Energy

Regulatory Commission over the past five years for nonfederal hydropower development at federal facilities, there is strong interest in the private sector to fill that role.[6] However, nonfederal development at these federal facilities may be limited at present owing to high technology costs and regulatory permitting barriers.

Conduit hydropower projects are constructed on existing water-conveyance structures, such as irrigation canals or pressurized pipelines, that deliver water to municipalities, industry, or agricultural water users. Although water conveyance infrastructures are not usually designed for energy purposes, renewable energy can be captured from them without the need to construct new dams or diversions. The aggregate hydropower potential from U.S. conduit systems is likely to be much less than that from NPDs or undeveloped streams. However, in a local context, the addition of hydropower to existing water conduits, many of which constitute aging infrastructure that is becoming more expensive to maintain, can provide a valuable new revenue source based on clean, renewable energy production. Recently enacted legislation has reduced some of the regulatory barriers that may have hindered full development of this energy resource.

Low-Impact New Development (LIND)

As noted above, a DOE-funded study analyzed over three million stream reaches in the United States and found that a tremendous opportunity exists for new hydropower development in stream segments that do not currently support hydroelectric facilities or other types of existing water infrastructure.[7] This study identified a resource potential of over 60 GW in these undeveloped streams. Developing a significant portion of this resource would require not only consultation with resource agencies and river stakeholders but also innovative hydroelectric power trains and civil works with reduced costs and low-impact environmental footprints.

Pumped-Storage Hydropower (PSH)

Worldwide, PSH is a proven and successful grid-scale energy storage and grid reliability solution and currently provides roughly 95% of U.S. electricity storage capability.[8] PSH uses pumps and turbines, or integrated pump-turbine machines, to draw off-peak, low-cost energy from the power system and pump water into higher elevation reservoirs. This energy is returned to the power system as the pumped water is released through turbines and into lower elevation reservoirs. It is called on for a wide range of cost-effective ancillary benefits and facilitates the integration of variable generation resources. Its flexibility can enable power systems to assimilate large thermal generating sources, accommodating 24-hour 7-day per week nuclear generating units and enabling coal-fired units to operate at loads that minimize costs and emissions. Although there are 22 GW of installed PSH capacity in the United States today, newer PSH technologies and facilities have been slow to achieve wide-scale domestic acceptance and adoption. As traditional PSH systems typically range in size from 500 MW to 2,000 MW, they face significant permitting, financing, and environmental “footprint” challenges. DOE is investigating the feasibility of modular PSH (m-PSH) that could resolve a majority of these challenges[9] and plans to support conceptual designs for new m-PSH systems.[10] In size ranges of 1 MW to 200 MW, closed-loop m-PSH systems could be more readily financed and realize broader acceptance with smaller reservoir requirements and minimal environmental impacts to aquatic systems owing to the lack of connectedness to natural water bodies. By leveraging existing infrastructure, they could be cost-effectively developed while still delivering the high value services of larger facilities.

Market and Other Impacts

Market share. With 78 GW of installed capacity, hydropower provides roughly 50% of all U.S. renewable electricity generation and provided approximately 7% (262 TWh) in 2013 of annual total U.S. electricity generation.[11] Hydroelectric generating facilities are in place in all 50 states, accounting for more than 25% of all the electricity generation in 13 western states and as high as 75% in Washington State.[12] Within the existing water infrastructure resource class, 12 GW (31 TWh/year) of hydropower resource potential can be added to the U.S. electrical grid from the development of NPDs,[13] and at least 5 GW (approximately 13 TWh/year) of additional capacity can be obtained by restoring and upgrading existing hydropower facilities.[14] There are 65 GW (340 TWh/year) of potential in undeveloped streams.[15] For context, approximately 90,000 homes can be powered by 1 TWh of electricity generation each year.[16]

Hydropower marketability. The U.S. context for hydropower development, like that of other low-carbon renewable energy technologies, is that it will be influenced by any future valuation of avoided carbon emissions or constraints on carbon emissions from fossil-fueled electric power production. Public and private hydropower development has been incentivized through a variety of state-level renewable portfolio policies, federal production tax credits, and federal investment tax credits.[17] As these policy factors evolve, so too will the market and demand for new hydropower capacity and energy. Future drivers for hydropower and water storage may include impacts of climatic change, with potentially increased water shortages—especially in the western states.

In many cases, hydropower development is associated with and complementary to the development of infrastructure for water supply, flood management, provision of minimum flow depths for commercial navigation, and maintaining reservoirs and streams for recreation. These multipurpose objectives, including hydropower energy production, were the impetus behind much of the federal water resources project development in the 20th century that now comprise 49% of U.S. hydropower capacity.[18] A significant portion of nonfederal hydropower capacity in the United States also resides at facilities that sustain water supply for agriculture and drinking water. As the stresses on water supplies and availability intensify in the 21st century, the demand for additional water supply development and reservoir water storage will grow and so may the associated development of hydropower capacity.

Many hydropower assets also provide electric utilities and power system operators with the ability to store significant energy as water behind dams and to strategically dispatch and regulate the release of this energy through powerhouses to improve the reliability, stability, efficiency, and value of power systems as a whole. These storage, ability to dispatch, and flexibility features—collectively labeled ancillary services—have always been used to great benefit within power systems but often have not been explicitly valued or monetized. As regional power markets evolve to explicitly value and, in some cases, compensate hydropower operators for ensuring the availability of these capabilities, these new explicit value and revenue streams may play a greater role in the feasibility, financing, and demand for new hydropower capacity. Existing hydropower assets are also affected by these evolving markets, such that in some cases, the primary role of an existing hydropower facility may evolve, in response to economic drivers, from one of energy supply to one of ancillary services provision.

Pumped-storage marketability. The marketability of ancillary services is a key factor in the development of new PSH assets. The feasibility of PSH development depends on two value streams: (1) a significant, predictable, and stable differential in energy prices or value that enables pumping during off-peak periods and generation during peak periods and (2) explicit markets or non-market mechanisms that compensate or incentivize pumped-storage asset owners for providing ancillary services to a power system.

The context for PSH development, including the availability of these two value streams, continues to evolve. PSH feasibility and development in the late 20th century was dependent primarily on the peak to off-peak or day-to-night energy price differentials. Development was also driven by the need for power systems to accommodate large additions of must-run base load nuclear generation, primarily in the eastern United States, to meet increasing energy demand. In contrast, PSH development in the 21st century will be dependent on marketability of ancillary services as well as the underlying and evolving need for power systems to manage increasing amounts of variable wind and solar generation, primarily in the mid-western and western United States. Outside the United States, the growth and utilization of pumped storage is already rapidly increasing, particularly in Asia and Europe. In Europe, more than 10 GW of pumped-storage capacity is planned to be commissioned between 2010 and 2020, with 40% of that total utilizing advanced pumped storage technologies with greater degrees of flexibility (either variable speed or ternary units).[19] Recently, DOE has supported some of the first detailed studies investigating potential benefits to local and regional U.S. electricity systems from the utilization of existing and new advanced pumped storage technologies.[20]

The prototypical large-scale pumped-storage facility remains a competitive storage technology in terms of capability and cost per unit of storage. Further, the relatively minimal environmental impacts on natural aquatic ecosystems associated with closed-loop pumped storage facilities can be a competitive advantage over more conventional store-and-release hydropower facilities located on large rivers. However, uncertainties in geotechnical engineering and construction; permitting; the lengthy schedule required for design, permitting, and construction; and related financial risk for such large-scale long-term projects limit the economic viability and feasibility for new development. This is especially true in comparison to the modularity, low cost, and relatively low-risk development pathway for new natural gas generating assets that provide flexibility and dispatchability within power systems, albeit with a significant carbon footprint and some fuel price risk. A decision by an electric utility or other energy stakeholder to pursue or support pumped-storage development as a strategy for power system stability, reliability, and resilience would require recognition and valuation of the long-term stability of pumped-storage operation and maintenance costs and the security that PSH provides.

Emissions from hydropower. The hydropower electricity generation process approaches near zero life-cycle greenhouse gas (GHG) emissions and criteria pollutant (NO_x, SO_x, and $PM_{2.5}$) emissions.[21] The potential for GHG emissions (mainly methane) from impounded water in both power-generating and non-power-generating dams is a complex issue and subject to ongoing research.[22] Recent research has shown that newly impounded tropical reservoirs in the southern hemisphere and reservoirs that receive extreme amounts of organic pollutant runoff from watershed activities may emit significant amounts of methane.[23] However, mature U.S. reservoirs are unlikely to be significant emitters of net GHG in the absence of such external conditions. Powering of NPDs and deployment of low-impact hydropower on undeveloped streams are unlikely to result in large reservoirs with hydraulic residence times or water quality conditions that would enable methane production.

Hydropower water use. Run-of-river hydropower facilities are essentially nonconsumptive users of water with minimal evaporative water loss above that of natural streams owing to the small hydraulic residence time. Large storage reservoirs, particularly those in arid regions of the United States, do experience measureable and accountable water losses from evaporation. However, the hydropower electricity generation process itself does not consumptively use water.

Hydropower economic impact. At least 172 companies, spread across 35 states, have manufacturing facilities in the United States to produce one or more of six major hydropower components (turbines, generators, transformers, penstocks, gates, and valves).[24] The hydropower industry supports over 55,400 direct jobs in the United States.[25] Overall the U.S. hydropower supply chain features more than 2,500 companies and employs approximately 300,000 American workers, both directly and indirectly.[26,27] Those companies include small, medium, and large firms and range from project developers to construction companies; architecture and engineering firms to electricians; and component manufacturers to biologists to operate, maintain, license, and ensure regulatory and environmental compliance for the roughly 100 GW of domestic hydropower, including pumped storage.

Technical Maturity

Modern hydraulic turbines and generators for large hydropower applications are highly optimized machines resulting from more than 100 years of technological evolution. Peak efficiencies of modern turbine-generator units typically exceed 90%[28]; however, refinements in efficiency are still needed with respect to biological performance and flexibility in response to operational and regulatory requirements. In deference to the large direct costs and opportunity costs of electrical or mechanical equipment failure, hydropower equipment vendors typically engage in their own research and development (R&D) to continuously improve the durability and reliability of the powertrain component designs for large hydropower applications.

Many turbine technologies are available in the worldwide marketplace to accommodate a variety of flow and head conditions that a potential site may present. Generating units at high-head and medium-head storage hydropower projects can typically be dispatched and provide ancillary services efficiently within a narrow range of flows and loads that align well with the capabilities and physical operating constraints of Francis and Pelton turbine technologies. Run-of-river hydropower projects typically experience a wider range of flow and generation dispatch that is well suited to Kaplan (adjustable blade pitch) or propeller turbine technologies, which can operate well above or below their design flow and power output with relatively little decrease in efficiency.

While powertrain technology is relatively mature, the adaptation and modification of hydropower generating facilities for environmental mitigation purposes is much less so. The environmental performance of turbine designs continues to show great promise for future improvements,[29] for example, in the form of blade-shape enhancements to reduce injury to fish and aeration into turbine flow passages to improve the water quality of releases. However, these evolving designs engender trade-offs among energy conversion performance, environmental performance, and technology cost that are not thoroughly understood. This is an active area for R&D, particularly in the U.S. market, where aging turbines are being replaced over the next 50 years and regulators and stakeholders are setting specific biological performance design and evaluation criteria. Ultimately, all new turbine designs require expensive physical model testing and field evaluation to validate environmental performance and achieve acceptance as a mitigation measure.

Environmental mitigation technology also includes equipment and structures for downstream and upstream fish passage (fish ladders, surface bypasses and collectors, turbine intake fish screens, removable spillways), weirs for tailrace aeration and reregulation, aerating turbines, oxygen diffuser systems, surface water pumps, and selective withdrawal structures for generation flows. These technologies are still primarily deployed through site-specific designs with little standardization. In addition to technology advancement through greater understanding of ecological response to mitigation designs, there are opportunities for environmental technology performance improvement and cost reductions from advancements in materials, manufacturing, construction, sensors, and deployment techniques.

Opportunities do exist to decrease the overall cost of LIND hydropower through multiple technology and project development pathways. Recent assessments indicate that many new hydropower facilities in the United States will be kilowatt and megawatt scale rather than gigawatt scale. Over 60%—almost 40 GW—of the undeveloped stream resource potential identified by Kao et al. (2014) would require low-cost turbines operating at less than 25 feet of head. However, significant new development in this size range is contingent on reductions in construction costs and improvements in the efficiency of licensing for small hydropower. While incremental advancements in powertrain technology may provide some cost reduction, innovations in project design, construction, and balance-of-plant equipment and structures will be equally important in accelerating deployment through cost reduction. Standard designs are not commonly available, so each new project typically has a unique and site-specific design, leading to increased design effort, environmental study and review, manufacturing costs, and operations and maintenance costs.

Strategic Priorities

The nation can take action to promote the development of novel technologies, improve operational procedures, and conduct rigorous analyses to assess the potential extractable energy from domestic waters as well as support industry initiatives to harness these renewable, emissions-free resources through environmentally sustainable and cost-effective electric generation.

The Role of Hydropower in National Priorities

The U.S. Administration's goal is to generate 80% of the nation's electricity from clean energy sources by 2035; reduce carbon emissions 26%–28% below 2005 levels by 2025; reduce carbon emissions 83% by 2050; lead the world in clean energy innovation; and stimulate jobs and economic growth with a clean energy economy.

National opportunities exist to improve the performance, lower the costs, and promote the development of new hydropower technologies within undeveloped streams and existing water infrastructure, including conduits and NPDs. In addition, the nation can continue to facilitate the development of rehabilitation technologies, environmental mitigation technologies, and energy-water decision support technologies that will sustain the production, capacity, and value of existing hydropower assets. Associated priorities include electric sector carbon intensity reduction, lower consumer electricity rates, job growth and catalyzing a robust new capability for modular hydropower manufacturing, improved grid reliability, and enhanced energy security and diversity.

These national opportunities may be framed in three broad categories as follows:

- **Defining, improving, validating, and standardizing the sustainability of hydropower technology.** Sustainability is a prerequisite for growth and future acceptance of hydropower. Existing and new hydropower assets must be ecologically, socioeconomically, and politically sustainable in addition to their primary function of energy production and power system services. The development of comprehensive, broadly accepted, and predictable indicators of sustainability to reward advancements in technology and improvements of the physical, ecological, and socioeconomic footprints of hydropower projects in the United States will be critical to supporting hydropower growth.
- **Lowering costs, risks, and timelines for hydropower technology and deployment.** Future opportunities abide in small-footprint hydropower development, but conventional powertrain and structural designs, construction, and installation techniques for hydropower assets require economies of scale and significant up-front investments to achieve grid parity. While the site-specific design and cost of conventional hydropower development from concept to operation is feasible for large-scale projects, a site-specific approach to small-footprint projects makes them expensive to deploy and maintain relative to their smaller revenue streams. Modular design enabling mass production economies as well as improved siting guidelines reducing permitting risk can help lower costs and improve prospects for deployment.
- **Quantifying, valuing, optimizing, and rewarding hydropower flexibility.** Hydropower assets, including pumped-storage assets, provide multiple ancillary services that enable successful operation of a dynamic and complex electricity grid. Because these services are seldom quantified, understood, valued, and rewarded, effort is required to characterize and optimize these services to help drive innovation and investment in hydropower technology and project development to keep pace with the requirements of the grid.

Major Challenges

Hydropower development and operations are intertwined with water resources stewardship, development, and management, which engender a complex set of interrelationships with public health and safety, water infrastructure, aquatic and terrestrial ecosystems, and regional economic development. These interrelationships typically are most evident in regulatory requirements to study and manage the site-specific public safety, ecological, and socioeconomic effects of development.

The site-specific nature of hydropower development is pervasive within the development process. This distinguishes hydropower from other electricity technologies that exhibit more standardization of machine and facility design with a relative indifference to deployment location and arises from the natural variability and diversity of the aquatic environment, requiring awareness and accommodation of multiple factors as follows:

- **Facility layout.** The hydrology[30] and physiography[31] of a hydropower facility, or any water control facility, influences the overall layout of a facility—specifically, the height and areal extent of dams and other civil structures required to impound water and control its release safely during normal operations and during floods. Physiography also includes the subsurface geologic conditions that may require site-specific geotechnical design to provide a suitable foundation for dams and other civil structures. These public safety aspects of facility design and operation, and the site-specific effort and expense they engender, are supreme and unavoidable in the development process.
- **Seasonal demand and availability.** Hydrology and physiography also include the time-varying availability of water as "fuel" and the elevation drop through which water flows (also known as hydraulic head) for hydropower production. These factors influence the energy revenue projections, technology type, size, and number of hydropower units contemplated in the design of a facility. This aspect of facility design may involve economic trade-offs in which site-specific energy efficiency and production may be compromised in favor of lower-cost standardized and modular technology or reductions in environmental consequences that would otherwise require expensive environmental mitigation technology.
- **Ecological and environmental conditions.** Hydrology and physiography also influence the presence of multiple species of flora and fauna and the ecological communities that may be affected by hydropower development and operations. The dynamics of water flow and water surface elevation that determine hydropower production are also primary factors that determine the availability and quality of habitat for flora and fauna. Historically, characterization of habitat, flora, and fauna and their response to hydropower development has been a site-specific undertaking, initiated once a site has been otherwise vetted. Issues that must be addressed in this regard include ecological responses to altered flow patterns and physical disturbance (temporary and permanent) to the streambed and adjacent lands. While a full consideration of these issues will always require some site-specific field study, relatively little attention has been given to identifying opportunities for systemic basin-scale studies. Such studies may be able to provide a comprehensive characterization of ecological impacts for development at multiple sites at lower per-site cost.
- **Socioeconomic considerations.** Hydrology and physiography also influence the socioeconomic context for infrastructure development. Specifically, the evolution of other uses of water (water supply, flood control, recreation, or navigation) and the compatibility of those uses with hydropower production can vary from site to site. As with ecological assessment, relatively few cases exist in which development efforts for a particular installation have been able to leverage basin-scale system and comprehensive studies of socioeconomic impacts. There may be opportunity to stimulate more robust basin-scale and regional planning studies with multiple hydropower sites included so as to avoid redundant effort and expense for each hydropower site.

These factors will continue to invoke site-specific concerns for existing and future hydropower deployment and will complicate efforts to standardize the technology, business, and regulation of hydropower development. The business and regulation of hydropower development have produced a plethora of unique dam, powerhouse, and machine designs as the understanding of the technology, its effect on the environment, and the science of such interactions have evolved. This diversity of design complicates efforts to typify hydropower technology, impacts of development, cost of development, developmental risks, and the overall value of hydropower development.

National RDD&D Opportunities

National opportunities exist to enable achievement of the aforementioned hydropower strategic objectives (sustainability, cost reduction, value to grid) across the three resource classes of existing water infrastructure, LIND, and pumped-storage hydropower.

Technology for Existing Water Infrastructure

Powering of NPDs can provide new low-impact capacity and energy. While industry is engaged in extensive powertrain research applicable to existing hydropower facilities, there is an opportunity to develop partnerships with industry in the high-risk area of quantitatively integrating environmental performance objectives—fish passage survival and water quality—into the hydromechanical design process of turbines. The tools to accomplish this will require advanced computational models of flow dynamics, fish kinematics, fish behavior and physiology, and gas transfer within turbine flow passages as well as laboratory and field scientific experiments to inform those models. Such design tools would require advanced physics-based turbulence modeling and high-performance computing power to incorporate fish passage and water quality objectives into the turbine design process.

Pursuit of powertrain research for existing infrastructure can accelerate the development of standardized modular machines for demonstration at NPDs and in canals, conduit systems, and other water conveyances. Standardized low-cost add-on modular turbine designs would need validated structural and dynamic load specifications, flow control reliability, and other critical safety and environmental characteristics for acceptance by federal and nonfederal owners and operators of NPDs and conduit systems.

In addition to powering of NPDs, there are opportunities to better understand the potential to increase power output at existing hydropower facilities through modernization and upgrades, such as improved sensors and controls, to more effectively manage water flow.

Technology for Low-Impact New Development

LIND represents the largest opportunity for hydropower development. Two key areas for national innovation are powertrain development and balance of plant (BoP), including civil works.

The nation could pursue research to develop standardized modular designs that minimize the manufacturing and installation costs of powertrain components. More importantly, such innovations could also minimize the physical footprint of the powertrain, which determines the BoP (auxiliary equipment and structures) costs and environmental disturbance. Powertrain innovations would likely include the use of advanced materials and manufacturing for powertrain components and innovative hydrodynamic, mechanical, and electrical design concepts to increase rotational speed and reduce turbomachinery size (diameter and length). Powertrain design innovations may also afford flexibility in selection of design objectives, such as initial cost minimization, efficiency over a range of head and flow rates, and durability or ease of replacement. Existing federal, university, or industry hydraulic test facilities and capabilities may potentially be leveraged to enable full-scale performance and reliability testing of the LIND powertrain technologies.

Pursuit of BoP R&D for LIND applications would complement the aforementioned powertrain R&D. Full-scale standardized facility designs, using innovative civil infrastructure configurations optimized to receive modular powertrains, could reduce civil costs, which can be up to 45% of project development costs for conventional project design.[32] Other innovations could include the use of advanced building materials, modularized structures, advanced construction techniques, and construction equipment. The reduced environmental footprint of these standardized project designs may decrease the complexity and cost of environmental review and licensing for LINDs.

Scientific, peer-reviewed validation of minimal environmental adverse impacts for specific LIND technologies will be crucial for acceptance of technology deployment by community, environmental, and regulatory stakeholders. The nation can choose to leverage national laboratory and university ecological science research capabilities to assess and predict the response of the aquatic environment to LIND technology deployment and validate those predictions in field demonstrations. An important aspect of research includes physical experiments to validate computational models of fish and flow-field interactions; models of stream-bed and stream flow alteration by LIND technology development and operations; as well as establishment of laboratory and field-testing protocols to validate the low-impact status of new technologies.

Technology for Pumped-Storage Hydropower

Assessments of pumped-storage technology and feasibility indicate that viable technology currently exists for large-scale pumped-storage development. The barriers to large-scale pumped-storage deployment are not technological; they arise from several other sources. These include state and federal policy constraints on development and operation, absence of financing for pumped-storage development, and absence of markets that compensate assets for ancillary services. Opportunities exist to develop detailed models that resolve pumped-storage value within wide-area models of power system operation and expansion, enabling power system planners to analyze the role that uncompensated or undervalued ancillary services play in power systems.

In addition to recent large-scale PSH modeling studies,[33] DOE conducted scoping studies of closed-loop, small-scale, and m-PSH feasibility in FY2014 and FY2015. Preliminary findings of those studies suggest that these project archetypes may provide valuable ancillary services and energy storage without the large environmental footprint or investment risk of large-scale pumped-storage. The nation could choose to undertake additional studies with industry consortia and national laboratories to develop consensus on future electric power system market settings, ancillary service roles, and required capabilities for distributed scale (<1 MW), municipal-industrial-commercial scale (1 to 20 MW), and utility-scale (20 to 200 MW) PSH technology and development.

National technology innovation may proceed along at least two pathways: (1) scalable PSH facility designs using commercial off-the-shelf pumps, turbines, piping, tanks, and valves to achieve reductions in PSH deployment costs and (2) hybrid PSH technology designs combining water storage with other forms of energy storage within energy and water delivery and collection systems. In addition, studies could be performed to assess which existing PSH facilities projects would be good candidates for upgrading from fixed (singular) speed to adjustable speed technology.

Supporting Research for Technology Development

DOE is developing a hydropower cost model (HCM) and database that include data collection, modeling, and analysis of the costs and performance of hydropower plants in U.S. markets. The objective of the HCM is to allow for an evaluation of contemporary hydropower project cost and performance with the primary goal of informing hydropower R&D priorities, with important but secondary benefits from providing industry with screening-level validated costing and performance evaluation tools. Baseline cost models can be used to predict total initial capital costs, operations and maintenance costs, periodic replacement costs, and "levelized" cost of energy (LCOE) of a hydropower project. Future national efforts can focus on development of an integrated design and assessment model. Such a model could incorporate the elements of the engineering design process into the economic feasibility assessment framework to account for trade-offs associated with technology selection or component design to support the evaluation of technology impacts on current and future hydropower LCOE.

Supporting Research on Market Barriers

Market and policy considerations, such as hydropower licensing and permitting delays and lack of valuation of hydropower in state renewable energy programs and/or regional markets, can affect the level of hydropower deployment. Opportunities exist to gather local, regional, and national data and conduct analyses on where regulatory policy and other market considerations are affecting deployment to inform policymaker decisions.

Technology Metrics and Impacts

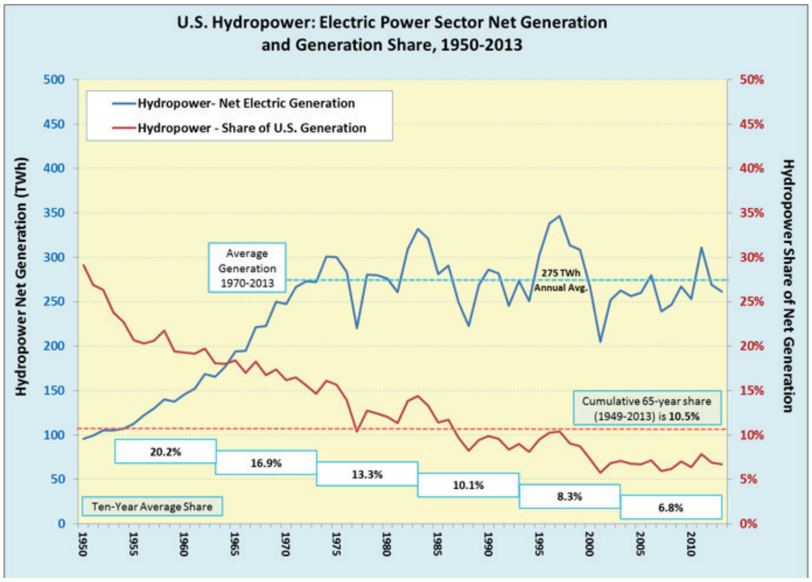
Historical Impact

Hydropower has long been a significant and reliable source of electricity for the U.S. economy. Just after World War II, U.S. hydropower provided nearly a third of U.S. electric power sector net generation (31% in 1949). Hydropower generation then more than doubled (175% increase) in 20 years, from 100 TWh/year in 1950 to 275 TWh/year in 1970. During that time, hydropower averaged over 20% of U.S. electric power sector net generation.[34]

The period of rapid construction of large hydropower facilities came to an end in the early 1970s (see Figure 4.L.1). Since then, hydropower generation has averaged 275 TWh/year for more than four decades, with annual variations owing to changes in rainfall and demand from year to year. Over the past decade (2004–2013), hydropower provided an average of 6.8% of U.S. electric power sector net generation.

Figure 4.L.1 U.S. Electric Power Sector Net Generation and Generation Share from Hydropower, 1950–2013. While average hydropower generation has remained constant over several decades, its share of generation has steadily decreased as U.S. power demand and net generation from all power sources have grown.

Credit: U.S. Energy Information Administration



Resource Characterization

Recent reports and maps assess the total technically recoverable energy available in the nation's powered dams, NPDs, and untapped stream reaches.[35] These resource assessments are pivotal to understanding hydropower's potential for future electricity production. While hydropower already contributes significantly to the nation's electricity supply, more potential resides in the nation's flowing waters to provide clean electricity to communities and cities across the United States.

There are three levels of resource assessments performed by the hydropower industry. Theoretical potential is the annual average amount of physical energy that is hypothetically available. Technical resource potential is the portion of a theoretical resource that can be captured by using a specific technology. Practical resource potential is the portion of the technical resource that is available when other constraints—including economic, environmental, and regulatory—are factored in. While there are many different ways that the nation can sustainably develop our hydropower resources for energy, other water uses, regulations, and interests must also be considered. Navigation, flood control, irrigation, recreation, municipal water supplies, and other environmental services can affect the availability of water resources for energy production, and competing uses are taken into consideration when developing water power resources.

Non-powered Dams (NPD)

An assessment of energy potential at NPDs in the United States,[36] compiled by DOE's Oak Ridge National Laboratory (ORNL), assesses the ability of existing NPDs across the country to generate electricity. The 80,000+ non-powered facilities represent the vast majority of dams in the country; more than 90% of dams are used for services, such as regulating water supply and controlling inland navigation, and lack electricity-generating equipment. The study found that the nation has over 50,000 suitable NPDs with the technical potential to add about 12 GW of clean, renewable hydropower capacity. The 100 largest capacity facilities—primarily locks and dams on the Ohio, Mississippi, Alabama, and Arkansas rivers operated by the U.S. Army Corps of Engineers—could provide 8 GW of power combined. Power stations can likely be added to many of these dams at a lower cost than creating new powered dam structures. Together, these NPD facilities could power millions of households and avoid millions of metric tons of carbon dioxide emissions each year.

New Stream-Reach Development

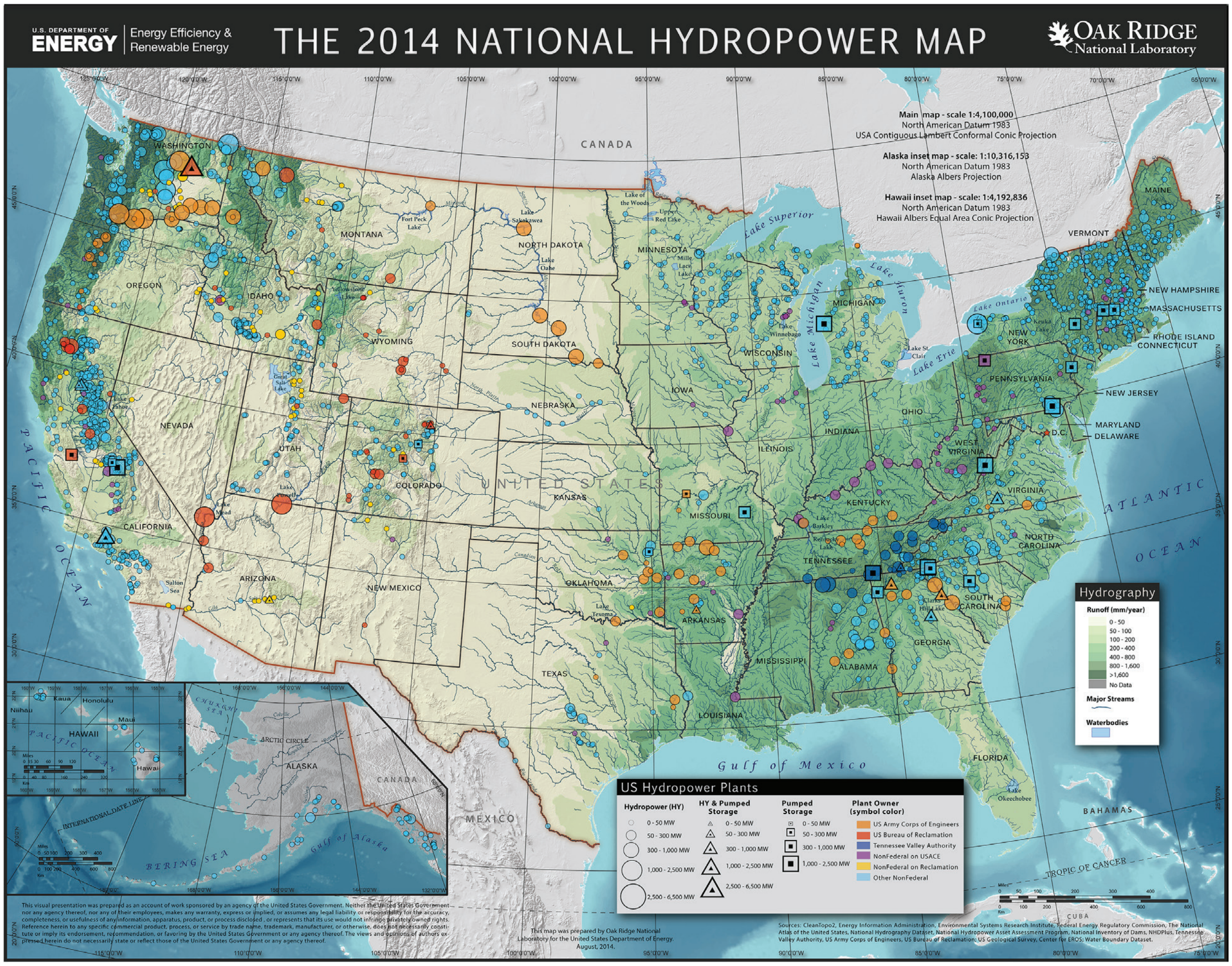
An assessment of energy potential from new stream-reach development in the United States led by DOE's ORNL provides a national picture of the remaining new hydropower development opportunities in U.S. rivers and streams.[37] This study leverages recent advances in national geo-spatial data sets to provide the highest fidelity national study yet, including the identification of social, economic, and environmental attributes of the stream reaches in addition to the technical power potential. The assessment concluded that the technical resource potential is 85 GW of capacity. When federally protected lands—national parks, national wild and scenic rivers, and wilderness areas—are excluded, the remaining potential is over 60 GW of capacity or 347 TWh/year of generation. A fact sheet summarizing the study's methodology and findings by state is available for download from DOE.[38]

Existing Infrastructure

ORNL created a geo-spatial database of existing hydropower assets so the nation can better understand its largest renewable electricity resource, integrate it with other resource assessments, and run analyses on a number of different data sets to help inform decision makers. The National Hydropower Map (Figure 4.L.2) shows the capacity of the existing fleet of hydropower facilities in the United States by ownership.[39]

Figure 4.L.2 The National Hydropower Map. This map integrates data from multiple data sources and provides the most current, detailed, and spatially comprehensive information for analyzing and visualizing existing U.S. hydropower assets. Existing hydropower asset data allows the nation to monitor its largest source of renewable electricity, integrate it with other resource assessments, and perform a wide variety of analyses that inform management decisions and policy.

Credit: Oak Ridge National Laboratory



Endnotes

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[2] Ibid.

[3] Zhang, Q.; Smith, B. T. 2015. Final Report: Demonstration Assessments of the Hydropower Advancement Project. Oak Ridge, TN: Oak Ridge National Laboratory (publication pending). http://hydropower.ornl.gov/research/hydropower/ . The DOE Hydropower Advancement Project sampled eight facilities nationwide for upgrade potential, finding an annual generation-weighted upgrade potential of 7.1 percent. Extrapolated to the 78 GW of hydropower-generating capacity in the United States, this yields a fleet-wide upgrade estimate of over 5 GW.

[4] Hadjerioua, B.; Wei, Y.; Kao, S. C. 2012. An Assessment of Energy Potential at Non-powered Dams in the United States. GPO DOE/EE-0711, Washington, DC. http://nhaap.ornl.gov/sites/default/files/NHAAP_NPD_FY11_Final_Report.pdf .

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[6] Federal Energy Regulatory Commission. Website. www.ferc.gov

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[11] U.S. Energy Information Administration. Table 7.2b Electricity Net Generation: Electric Power Sector. June 2014 Monthly Energy Review. DOE. June 25, 2014. http://www.eia.gov/totalenergy/data/monthly/

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[30] Hydrology is the science that encompasses the occurrence, distribution, movement and properties of the waters of the earth and their relationship with the environment within each phase of the hydrologic cycle (USGS).

[31] Physiography is the study of features and attributes of earth's land surface, including the area, surface topography, existence of lakes and wetlands, altitude, and land slope of watersheds affecting surface-water runoff and the amount and nature of chemicals and sediments in the water stream (USGS).

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Acronyms

BoP	Balance of Plant
DOE	Department of Energy
EIA	Energy Information Administration
FERC	Federal Energy Regulatory Commission
FY	Fiscal Year
GHG	Greenhouse Gas
HCM	Hydropower Cost Model
LCOE	Levelized Cost of Energy
LIND	Low-Impact New Development
m-PSH	Modular Pumped-Storage Hydropower
NOx	Nitrogen Oxides
NPD	Non-Powered Dam
ORNL	Oak Ridge National Laboratory
$PM_{2.5}$	Particulate Matter (2.5 microns in size or less)
PSH	Pumped-Storage Hydropower
SO_x	Sulfur Oxides
TWh	Terawatt-hour

Glossary

Ancillary Benefits	Grid services provided by a power generation facility that support the transmission of electricity from its generation site to the customer. May include load regulation, spinning reserve, non-spinning reserve, replacement reserve, and voltage support.
Draft Tube	A water conduit, which can be straight or curved depending upon the turbine installation, which maintains a column of water from the turbine outlet and the downstream water level.
Francis Turbine	A Francis turbine is a type of reaction turbine that has a runner with fixed buckets (vanes), usually nine or more. Water is introduced just above the runner and all around it and then falls through, causing it to spin. Besides the runner, the other major components are the scroll case, wicket gates, and draft tube.
Head	Vertical change in elevation, expressed in feet or meters, between the head (reservoir) water level and the tailwater (downstream) level.
Hydrology	The science that encompasses the occurrence, distribution, movement and properties of the waters of the earth and their relationship with the environment within each phase of the hydrologic cycle.
Impulse Turbine	The impulse turbine generally uses the velocity of the water to move the runner and discharges to atmospheric pressure. The water stream hits each bucket on the runner. There is no suction on the down side of the turbine, and the water flows out the bottom of the turbine housing after hitting the runner. An impulse turbine is generally suitable for high head, low flow applications.
Kaplan Turbine	A type of propeller reaction turbine that generally has a runner with three to six blades in which the water contacts all of the blades constantly. With the Kaplan, both the blades and the wicket gates are adjustable, allowing for a wider range of operation.
Low Head	Head of 66 feet or less.
Pelton Turbine	A pelton wheel is a type of impulse turbine that has one or more free jets discharging water into an aerated space and impinging on the buckets of a runner. Draft tubes are not required for impulse turbine since the runner must be located above the maximum tailwater to permit operation at atmospheric pressure
Physiography	The study of features and attributes of earth's land surface, including the area, surface topography, existence of lakes and wetlands, altitude, and land slope of watersheds affecting surface-water runoff and the amount and nature of chemicals and sediments in the water stream.
Pumped Storage	A type of hydropower that works like a battery, pumping water from a lower reservoir to an upper reservoir for storage and later generation.

Reaction Turbine	A reaction turbine develops power from the combined action of pressure and moving water. The runner is placed directly in the water stream flowing over the blades rather than striking each individually. Reaction turbines are generally used for sites with lower head and higher flows than compared with the impulse turbines.
Runner	The rotating part of the turbine that converts the energy of falling water into mechanical energy.
Scroll Case	A spiral-shaped steel intake guiding the flow into the wicket gates located just prior to the turbine.
Tailwater	The water downstream of the powerhouse or dam.
Ultra Low Head	Head of 10 feet or less.
Weir	A low dam built across a river to raise the level of water upstream or regulate its flow
Wicket Gates	Adjustable elements that control the flow of water to the turbine.

See also: **Glossary of Hydropower Terms**
http://energy.gov/eere/water/glossary-hydropower-terms