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The potential of water power in the fight against global warming in the US

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ABSTRACT

The leading cause of climate change today is the burning of fossil fuels related to energy production. One approach to reducing greenhouse gas emissions, therefore, is to more actively switch to renewable technologies in the production of electricity, and reduce the use of fossil fuels in electricity production. This is the goal of renewable portfolio standard (RPS) legislation, currently in effect in 28 states across the country. In this paper we discuss the potential for water power development as one method to reduce US greenhouse gas emissions. We look at the potential from (1) new small/micro hydropower dams, (2) uprating facilities at existing large hydropower dams, (3) new generating facilities at existing non-hydropower dams, and (4) hydrokinetics. We analyze this potential by type, by state, and by its ability to satisfy current RPS goals. Finally, we consider the cost-effectiveness of developing these sources of water-based energy. We find that while water power will never be the complete answer to emissions-free energy production, a strong case can be made that it can be a useful part of the answer.

1. Introduction

Global warming is an increasingly prominent international concern. Reducing the greenhouse gases that contribute to global warming has therefore become an important public policy objective. Numerous proposals have been suggested to reduce greenhouse gas emissions, including implementing cap and trade markets, applying carbon taxes, and encouraging research and development into promising new energy production technologies such as fuel cells, ocean power, and ethanol. We are currently at the vanguard of discovering which of these methods will prove fruitful, politically palatable, and cost-effective in reducing greenhouse gases. As we proceed in the effort to reduce global warming, it is worthwhile to continue exploring all of our available options, to help diversify avenues of approach into this difficult and pressing problem.

The leading cause of climate change today is the burning of fossil fuels related to energy production. Another approach to reducing greenhouse gas emissions, therefore, is to more actively switch to renewable technologies in the production of electricity, and reduce the use of fossil fuels in electricity production. This is the main objective of the renewable portfolio standards (RPS) that are increasingly being passed in many states across the United States. In 2003 only three states had passed legislation implementing RPS, but by 2007 the number had grown to 28, and in that year even the House of Representatives introduced legislation to implement a federal-level RPS at 15% of electricity generation.

Renewable alternatives to fossil fuel use include solar, wind, geothermal, biomass, and hydroelectric power. Currently, hydroelectric power is far and away the main renewable in use, satisfying two-thirds of all renewable electricity production in the United States. It is a proven technology, with a number of benefits besides just emissions-free electric power. Hydropower is also entirely domestic, not relying on foreign imports for production, it is decentralized, and it has excellent reliability and energy efficiency properties. Hydropower is not without its detractions, of course, the main concern being its impact on fishery resources and local riverine ecosystems. But what is often underemphasized is that there are gradations of hydropower production, and "small" or "micro" hydropower systems have extremely minimal riverine impacts. Electric power is also being developed from non-traditional water sources (also called "hydrokinetics"), including river and ocean currents. Even the larger, more traditional hydropower plants that do have negative riverine impacts, have been researched in recent years and promising improvements in turbine construction and refurbishment (also called "uprating") are leading to significant reductions in their environmental externalities. Ultimately, hydropower production in all its gradations needs to be analyzed and subject to benefit–cost considerations in order to determine its appropriate place in the pantheon of renewable alternatives to fossil fuel energy production.

In this paper we discuss the potential for hydropower development as one method to reduce greenhouse gas emissions.

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Table 1
US electricity generation percentages, by sector, 1950–2005

Year	Coal	Petroleum	Natural gas	Nuclear	Biomass	Geothermal	Solar	Wind	Hydro
1950	46.25	10.10	13.34	0	0.12	0	0	0	30.20
1955	54.76	6.75	17.32	0	0.05	0	0	0	21.12
1960	53.09	6.32	20.81	0.07	0.02	0	0	0	19.69
1965	53.94	6.12	20.93	0.35	0.03	0.02	0	0	18.61
1970	45.89	12.00	24.29	1.42	0.02	0.03	0	0	16.35
1975	44.40	15.05	15.61	8.98	0.01	0.17	0	0	15.78
1980	50.73	10.74	15.12	10.97	0.02	0.22	0	0	12.19
1985	56.70	4.05	11.81	15.52	0.06	0.38	0	0	11.50
1990	52.47	4.17	12.27	18.99	1.51	0.51	0.01	0.09	9.64
1995	50.97	2.22	14.79	20.08	1.70	0.40	0.01	0.09	9.27
2000	51.72	2.93	15.81	19.83	1.60	0.37	0.01	0.15	7.25
2005	49.64	3.02	18.69	19.28	1.34	0.36	0.01	0.44	6.67

Source: Energy Information Administration.

Hydropower will never be the complete answer to emissions-free energy production, but a strong case can be made that it can be a useful part of the answer. In this paper, we document the possible sources of additional hydroelectric power production across the United States, including potential coming from (1) new small/micro hydropower dams, (2) uprating facilities at existing large hydropower dams, (3) new generating facilities at existing non-hydropower dams, and (4) hydrokinetics.[1] We look at this potential by type and by state. We then translate this increased hydropower production into emissions reductions, in total and in comparison to RPS goals across the country. Finally, we present a discussion of the benefit and cost considerations of developing this hydropower potential. What we find is that the qualitative benefits of hydropower production, after internalizing all the documented positive and negative externalities, has the real potential to outweigh the costs. More (particularly quantitative) research is needed, but a strong case can be made that increasing attention should be paid to hydropower production in our portfolio of strategies to reduce greenhouse gas emissions and address climate change.

2. A history of hydropower

Hydroelectric power was first developed in the late 19th century.[2] In the United States some of the first street lights to be powered by hydroelectricity were near Niagara Falls, in New York. Once the technical viability of hydroelectric power was established, hydropower production grew rapidly in the United States until, in the early 1900s, hydropower accounted for more than 40% of total US electricity supply (and more than 75% of electricity supplied in the West and Pacific Northwest). Large hydroelectric dams like the Hoover and the Grand Coulee were built in the 1930s, bringing the US economy much-needed depression-era jobs, and eventually supplying the US industrial sector with the power necessary to ramp up armament production in preparation for World War II. After the Second World War, hydropower's dominant role in the nation's overall electricity supply diminished. Today, hydropower generates between 7% and 10% of total US energy supply (see Table 1), and this percentage continues to diminish as a result of two primary forces: the lack of additional viable sites for new large hydropower development projects, and the increasing regulatory stringency of non-federal hydropower licenses, which, in an effort to protect riverine ecosystems, have often mandated reduced hydropower production levels (Kosnik, 2008).

In 2006 conventional hydropower capacity in the US was at 80,000 MW, or enough power to supply approximately 80 million homes per year.[3] Approximately 65% of this capacity is publicly owned (at both the federal and non-federal levels), and around 35% is privately owned (by both utilities and non-utilities).[4] The location of hydropower generation capacity in the US is not uniform (Table 2)—nearly one-third of the nation's hydroelectric power production is located in the state of Washington alone, and more than half is located in the Pacific Contiguous Census Division, which includes California, Oregon, and Washington. This heterogeneous geographic availability of river resources in the US already affects the RPS in different states and will likely affect future interest in any type of hydropower reform or development. Around the world, hydropower's share of global energy production is higher than in the US, averaging 17% (Table 3), and in some countries, such as Canada, Brazil, Norway, and New Zealand, hydropower is actually the primary source of electricity production.

3. The mechanics of hydropower

Hydroelectric power is produced through the kinetic energy of falling water. Water is first diverted from a riverway, or impounded by a dam, and is then steered through a penstock to a turbine, which rotates from the force of the falling water. The amount of water flow along with the degree of water pressure (or "head") together determines the amount of mechanical energy generated by the turbine. Generators are connected to the turbines that rotate and turn the mechanical energy into electrical energy, which is then conducted along transmission lines to the ultimate point of use. There are three general size classifications of hydropower plants: large, small, and micro.[5] Large hydropower

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[1] We do not consider any potential coming from the construction of new large (i.e. traditional) hydropower dams.

[2] Harnessing water for purposes other than electricity generation, such as for irrigation, flood control, or dependable supply (as with the Roman aqueducts), has, of course, a much longer history.

[3] One megawatt of power roughly translates into enough energy to satisfy the average power needs of 1000 homes.

[4] If measured by number of plants (as opposed to capacity) the numbers come out nearly reversed: 31% of projects are controlled through public ownership, while 69% of projects are controlled through private firms.

[5] The exact numerical definition of these size classifications can vary by publication (also, "micro" is sometimes referred to as "low"). The following definitions are based on data categorizations used by the US Department of Energy.

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Table 2
Percent US hydropower production, by state (2006)

State	Total
Alabama	2.51
Alaska	0.42
Arizona	2.35
Arkansas	0.54
California	16.61
Colorado	0.62
Connecticut	0.19
Delaware	0.00
Florida	0.07
Georgia	0.89
Hawaii	0.04
Idaho	3.89
Illinois	0.06
Indiana	0.17
Iowa	0.31
Kansas	0.00
Kentucky	0.90
Louisiana	0.25
Maine	1.48
Maryland	0.73
Massachusetts	0.52
Michigan	0.53
Minnesota	0.20
Mississippi	0.00
Missouri	0.07
Montana	3.50
Nebraska	0.31
Nevada	0.71
New Hampshire	0.53
New Jersey	0.01
New Mexico	0.07
New York	9.45
North Carolina	1.33
North Dakota	0.53
Ohio	0.22
Oklahoma	0.22
Oregon	13.09
Pennsylvania	0.98
Rhode Island	0.00
South Carolina	0.62
South Dakota	1.17
Tennessee	2.68
Texas	0.23
Utah	0.26
Vermont	0.53
Virginia	0.47
Washington	28.35
West Virginia	0.54
Wisconsin	0.58
Wyoming	0.29

Source: Energy Information Administration.

Table 3
Hydropower's share of world electricity production, by region (2004)

Region	% Hydro
North America	13.21
Central and South America	66.36
Europe	15.63
Eurasia	18.84
Middle East	2.96
Africa	16.86
Asia and Oceania	12.70

Source: Energy Information Administration.

plants are those that generate more than 30 MW of power, small hydropower plants generate between 30 and 1 MW of power, and micro hydropower systems produce less than 1 MW of power, enough to supply a small village or town.

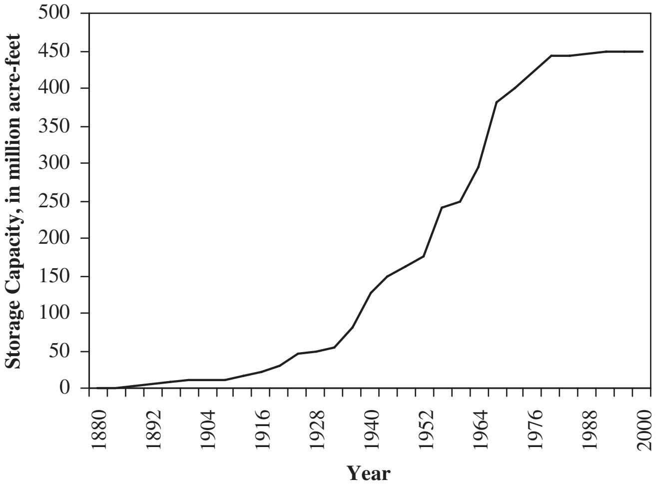

Fig. 1. Reservoir storage capacity in the US (1880–2000). *Sources*: US Geological Survey, Circulars 1186 and 1261.

4. Background

Large hydropower plants constitute most of the current capacity of hydropower production worldwide, and so it is the discussion of these projects that is implied whenever arguments are made over the relative benefits of hydropower capacity development. The most contentious aspect of large hydropower dams is their environmental impacts on local rivers, most specifically, on fish mortality.[6] When a large hydropower facility is built, the composition of fish in a river changes. Net numbers of fishery resources actually may not diminish (as certain fish thrive in reservoirs and the altered water flows downstream of a dam), but indigenous fish, particularly those that migrate (such as salmon, trout, sturgeon, lampreys, shads, and others), are often severely impacted by the obstacle of a large dam. The dam blocks the passage of adult fish migrating upstream to spawn, as well as the movement of juvenile fish downstream towards the ocean. Because upstream passage is primarily undertaken by strong, healthy, powerful adults, methods that have been developed to pass fish upstream, for example fish ladders, fish elevators, or fish lorries, are relatively effective. It is the downstream migrating juveniles that are the biggest mortality risk of large dams, and methods to pass them (including spillways and bypasses) are not, as yet, entirely effective. Significant declines in native fish species due to large dam development have been cited, for example, along the Columbia River (Connor et al., 2003), the Snake River (USACOE, 2002), and the Mississippi River (Ickes et al., 2001).

The construction of large, traditional hydropower plants has essentially stalled in the US because of these negative riverine impacts.[7] Fig. 1 shows the annual figures for total dam storage capacity in the United States from 1880 until 2000; this graph makes clear the history of large dam construction from its initial viability and take-off around the turn of the 20th century, until its stagnation around the early 1980s. Since that time there have been very few new large dams constructed anywhere in the United States. Although many under- and less-developed nations continue to build new large hydropower dams (prominent

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[6] Other issues that are often raised, such as stream-bank erosion and water turbidity, are often also important because of their effects on fish mortality levels.

[7] Attempts have been made (Loomis, 1998, 1996; Loomis et al., 2000) to empirically measure these impacts through contingent valuation analysis and the results are often highly significant.

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examples of which include the Three Gorges in China and the Ataturk Dam in Turkey), international funding for such projects has largely dried up. The World Bank, in its dam-funding heyday in the early 1970s and 1980s, approved more than eight dam-related projects per year; today they approve less than one per year. In the United States, the federal bureaucratic agency responsible for hydropower dam licensing, the Federal Energy Regulatory Commission (FERC), denied an operational license for a traditional hydropower project for the first time in its over 70-year history in 1993, essentially because of the dam's negative riverine impacts. The construction of new, large, hydropower dams is environmentally harmful, politically unpalatable (at least in the United States), and simply not viable as an option for increasing renewable energy alternatives.

However, that is not the end of the story for hydropower. The negative riverine impacts of hydropower dams diminish with plant size, ceteris paribus.[8] Small and micro hydropower plants, at generation capabilities of less than 30 MW, have extremely minimal riverine impacts. Significant power can be generated with flows of just two gallons per minute, or from drops as small as two feet, implying that few small or micro hydropower projects require all of the water available in a stream to be dammed or diverted. This allows a substantial amount of river flow to remain in-stream, available to maintain riverine integrity. Small and micro hydropower systems, therefore, generate emissions-free electric power, without much of the additional negative environmental externalities of large dams. And there are other benefits too. Small and micro hydropower is much more reliable than alternative renewable, such as solar or wind power. The sun goes down at night and for much of the winter, and in any given day can spend a lot of time behind cloud coverage. Wind is also variable, intermittent, and unpredictable. Small and micro hydropower sites can be winterized to provide power throughout the year, when these other renewables cannot be counted on (Fig. 2). Additionally, even very small micro hydro systems, at about 18 kWh, will produce more power than many (also more expensive) photovoltaic systems. Small and micro hydropower development is taking place worldwide; China now has more than 43,000 small hydro facilities producing more than 19,000 MW of electricity (MNRC, 2004), and more than 100 other countries have constructed small hydro plants in recent years (Voros et al., 2000). In the United States, the Department of Energy (DOE) completed a study in 2006 on the possibilities for small and micro hydropower development across the US and found a total available capacity, for facilities generating *less than* 30 MW of power, of more than 275,000 MW.[9] This is nearly three times our current hydropower production. This capacity is also distributed across the United States (Fig. 3).

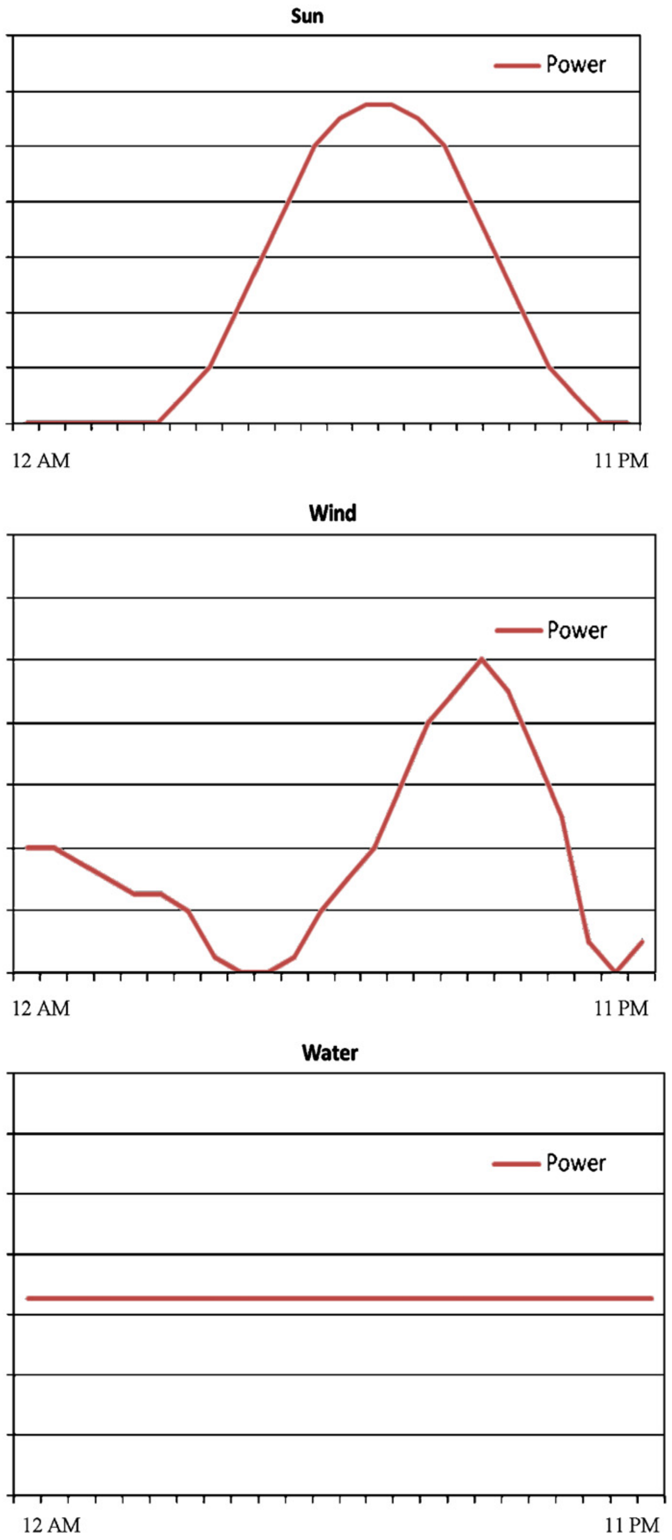

Fig. 2. Typical generation service over a 24 h period from sun, wind, and water. *Source*: Davis (2003). *Note*: An anonymous reviewer pointed out that the fluctuations in wind power can be even more severe when measured over weeks, as opposed to just 24 h.

And this is only small hydro. While the benefits of new large hydro development is questionable in the United States, efficiency improvements at existing dams, or what is called "uprating", has the potential to increase hydropower production by as much as 50% (Veltrop, 1997). This is without any increases in reservoir size or dam size, while, through improved turbine technology, at the same time *diminishing* impacts on fish mortality levels. The increasing cost of energy and the need to find fossil fuel alternatives, combined with the concern over fishery impacts of large dams, has led to a considerable acceleration of research over the last decade into technological improvements for fish passage

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[8] There are other factors besides size that can affect the environmental impact of a hydropower dam, most importantly, mode of operation. If a dam is operated with a fluctuating storage reservoir, while this will generate more electricity (as well as other ancillary benefits) at more valuable times, it will also lead to greater environmental harm than a purely run-of-river (i.e. non-storage) dam operation. Small dams tend to have less environmental impact than large dams not just because of their size but also because in practice they often tend to be run-of-river plants.

[9] The report actually produces estimates of "mean annual power", which is not the same as capacity. Capacity is based on installed turbines, while mean annual power is based on flow conditions. As is done in other DOE reports, we convert mean annual power into capacity by a multiplicative factor of two.

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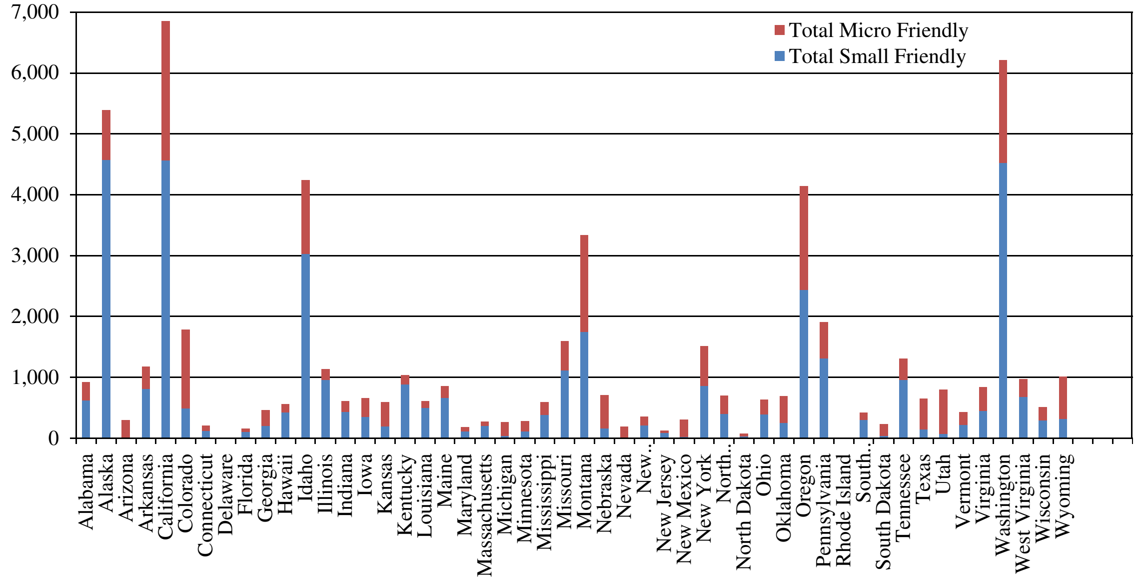

Fig. 3. US small and micro hydropower potential, by state (MW).

and protection.[10] At Wanapum dam in Washington State, for example, a new advanced design turbine is providing increases in power output of 14%, a water use efficiency gain of 3%, and fish passage survival of 97.82%—a record (Brown, 2006). These new turbines are admittedly expensive, but as the cost of energy increases, such options become more cost-effective. Uprating has the added benefit of extending the service life of many power plants, making it even more cost-effective over the long run. The Low Impact Hydropower Institute, a non-profit organization "dedicated to reducing the impacts of hydropower generation",[11] has developed a program that provides certification for development of hydropower at existing dams that can be done in an environmentally acceptable way. As of 2007, they have certified 28 facilities, in 19 states, producing nearly 2000 MW of power.

It is also possible to develop new hydropower facilities, but at already existing dams. The National Inventory of Dams documents over 79,000 dams in the United States. Less than 3% of these currently have developed hydropower capacity; most of the dams were built for other purposes including irrigation, navigation, municipal water supply, or flood control. Adding hydropower facilities to these dams would add relatively little in additional negative environmental externalities, but has the potential to generate substantial increases in renewable energy.[12] Not all facilities could profitably be developed, of course, and studies would need to be conducted at the individual site level to determine capacities and realized environmental effects, but even a slight increase in development of existing dams for hydroelectric power production could lead to large increases in renewable energy production. There is a history of cost-effective private development of new hydropower facilities at existing federal dams (Bahleda and Hosko, 2007; Perspectives on Hydropower: Federal Organizations Share Views, 2003). Such development could be repeated and encouraged to reduce emissions generated from fossil fuel-based energy production.[13]

Finally, the future holds promise with a number of emerging technologies that utilize river and ocean water to develop emissions-free, environmentally benign electric power. Hydrokinetics is the study of fluid in motion, and it is being developed to access the energy in river, tidal, and ocean currents to generate electric power. Early estimates are that these sources could provide, at a minimum, an additional 23,000 MW of power in the United States (Bahleda and Hosko, 2007). Hydrokinetic and wave energy technologies require no impoundments, so the environmental externalities associated with dam construction and reservoir creation not relevant. While these technologies are still very new, prototypes are popping up with increasing frequency, in New York, Washington, Oregon, California, and Florida. In 2006 FERC received over forty applications for preliminary permits for potential hydrokinetic projects, and in 2007 FERC issued a notice seeking public comment on how to streamline permitting and licensing of these new facilities. In this paper we will not be analyzing these new technologies in any depth, but they are worth noting for the additional renewable energy that they could provide, based on the power of water.

In the next section we review the additional electricity generating potential of hydropower from the following sources: (1) new small/micro hydropower dams, (2) uprating facilities at existing large hydropower dams, (3) new generating facilities at existing non-hydropower dams, and (4) hydrokinetics.

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[10] The DOE's Advanced Hydropower Turbine System Program is one example of the R&D efforts now underway to design turbines for large dams that will reduce fish mortality levels (Cada, 2001).

[11] Information can be found on this group at: http://lowimpacthydro.org/.

[12] For example, the cities of Boulder, Colorado, Wichita, Kansas, Los Angeles, California and Sitka, Alaska, all added hydro facilities to the control works of existing municipal water supply systems in the 1980s and 1990s. Water flows in a typical municipal water supply system must be relieved of pressure before they can enter treatment stations and distribution facilities. Many plants do this with pressure reducing valves, but a perfectly acceptable alternative is to convert the pressure to electricity with small hydro turbines. Today, Boulder generates close to 4 MW of power, Wichita 500 kW, Los Angeles 39.6 MW, and Sitka 1.5 MW of power from such facilities (Gledhill, 2002; Busse et al., 1992).

[13] The 2005 Eneregy Bill includes incentive payments of 1.8 cents per kWh for up to 10 years (capped at $75,000 per facility per year) for "qualified hydroelectric facilities" at which a turbine or other generative device is added to an existing dam or conduit.

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5. Data

5.1. Small/micro

In the early 1990s the DOE began a concerted effort to assess the total amount of undeveloped hydropower resources within the United States. This was part of a larger National Energy Strategy, intended to identify all available energy resources within the United States that could help satisfy the economy's growing energy demands. In 1998 the first report came out (USDOE, 1998), concentrating on conventional (i.e. large) hydropower capacity development. It was based on a compilation of previously identified developable sites, the source data coming from existing state-level and federal-level databases. Understanding that environmental concerns limited the development of much of this reported potential, the next report (USDOE, 2004) concentrated on identifying new sites with the potential for smaller scale development. The unique assessment method identified new, as well as previously known, sites. It combined digital elevation models with GIS tools to estimate the power potential of a mathematical analog of every natural stream segment in the country. The gross power potential of each site was then defined according to the annual mean flow rate of the associated reach and the gross hydraulic head (which equaled the elevation difference between the upstream and downstream ends of the, on average, 2-mile reach).[14]

This gross power "potential" was then revaluated in 2006 (USDOE, 2006) along a number of dimensions. First, the gross power potential was reduced by that which was located in excluded zones; land protected from development by federal statutes and policies, or because of known environmental sensitivities. Areas excluded included national parks, national monuments, areas around and including national wild and scenic rivers, national preserves, national wildlife refuges, national wilderness areas, and wildlife management areas. The remaining power potential is referred to as gross power "available".

Next, the 2006 report identified all available resources by their feasibility. The practical feasibility of development at each site was based on three criteria: (1) site accessibility, (2) load or transmission proximity, and (3) the existence of land use and environmental sensitivities that would make development unlikely. The third criterion was based on data from the Conservation Biology Institute. It includes areas with some form of permanent protection from conversion of natural land cover, for example, ecological reserves, botanical reserves, national recreation areas, scenic recreation and research areas, conservation easements and local land trusts, fish and game management areas, military reservations, state memorials, and state parks.[15]

Finally, ultimate estimates of the power potential at each site were made based on a rigorously environmentally "friendly" development model. The model was of a penstock running parallel to the stream, culminating in a powerhouse whose tailwater returned the working flow to the stream. No dams or impoundments of any kind that would obstruct the watercourse of form a reservoir were assumed. The model also made sure to never utilize more than half the water flow of the waterway for electricity generation. Penstock lengths were limited as well. The final estimates produced by this model, therefore, were extremely conservative, but also extremely environmentally sensitive.[16]

Table 4 reproduces the results of these analyses. The small and micro "potential", "available", and "friendly" gross power numbers are presented for each state in the country.[17] There is a total of more than 180,000 MW of small hydropower capacity available for development, 90,000 MW of micro hydropower. Concentrating on just the most environmentally sensitive production, there is a combined total of nearly 60,000 MW, a 75% increase from current renewable hydropower production levels. The western states continue to dominate in environmentally friendly gross power, as they do with potential gross power (which can more easily be seen in Fig. 3), but smaller resources are still located in every state in the country. There is clearly a large potential for small and micro hydropower development across the United States.

5.2. Uprating

Uprating is the improvement of power output at a hydropower facility through efficiency enhancements, often through turbine replacement. Estimates of the uprating potential of current hydropower facilities in the US vary widely. Some have been given as low as 8% of current output (USDOE, 1998), others as much as 50% of current output (Veltrop, 1997).[18] Table 5 provides a breakdown, by state, of the low estimate produced by the DOE. This is a conservative estimate as it does not include any pumped-storage facilities, it is based on estimates from conventional hydropower capacity only, and it is static as of 1998—important technological breakthroughs in turbine efficiency have been made in the last decade since the report was published. The report provides an estimate of nearly 7000 MW of additional capacity from efficiency improvements.

The DOE report then goes further, by taking the initial uprating "potential" estimates and reducing them by environmental considerations, such as whether the location of the facility is considered wild or scenic, whether the location has cultural value, protected fish or wildlife presence, geologic value, or historical value. After reducing the gross potential by these considerations, the final environmentally "friendly" uprating total estimated by the DOE is nearly 4000 MW. As usual, much of this potential is located in the West, in states such as Idaho, California, Montana, and Washington. But there is still uprating capacity available in many other areas. The potential to benefit from uprating capacity improvements is nationwide.

5.3. New generation at existing dams

The DOE's 1998 report also included estimates of the power potential at "developed" sites (i.e. those that already have some type of developed impoundment or diversion structure), but that are not currently producing any power. This report concentrates on conventional, or relatively large, hydropower facilities only, and so the estimates given are certainly conservative of any total additional hydropower potential available nationwide.[19] The National Inventory of Dams documents thousands more dams than were considered in the DOE's 1998 report, many of which are likely viable for, at least small, hydropower capacity installation. The first column in Table 6, therefore, presents the DOE's gross

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[14] The official equation used was $P=\kappa H(Q_i+Q_o)/2$, where $P=$ power in kilowatts, $\kappa=$ the constant 0.08, $H=$ hydraulic head in feet, $Q_i=$ flow rate at the upstream end of the stream reach in cubic feet per second, $Q_o=$ flow rate at the downstream end of the stream reach in cubic feet per second.

[15] I thank an anonymous reviewer for pointing out that if coal-fired plants were similarly barred from polluting these areas, a significant portion of current coal generation would have to be closed.

[16] These final estimates are conservative also because they do not include any submerged, hydrokinetic potential of the identified sites.

[17] Note that the terminologies "potential," "available," and "friendly" are those of the author and not necessarily of the DOE.

[18] In 1992 FERC estimated the uprating potential at 20% of current output (Barnes, 1992).

[19] For example, it does not include the potential from sources such as adding hydropower to conduits in existing municipal control works.

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Table 4
US small and micro hydropower potential, by state (MW)

State	Small potential	Small available	Small friendly	Micro potential	Micro available	Micro friendly	Total friendly
Alabama	1708	1608	622	1672	1640	300	922
Alaska	98,274	54,478	4568	29,102	16,820	820	5388
Arizona	2980	908	20	2300	1738	280	300
Arkansas	2190	1798	810	1756	1552	370	1180
California	34,494	16,302	4566	7258	5038	2282	6848
Colorado	9204	6198	490	4856	3808	1292	1782
Connecticut	472	426	122	304	274	88	210
Delaware	28	20	8	14	10	4	12
Florida	426	330	102	428	316	54	156
Georgia	1832	1242	202	1568	1398	258	460
Hawaii	3410	3390	428	310	308	132	560
Idaho	23,022	12,234	3030	6156	4586	1214	4244
Illinois	750	636	954	822	706	182	1136
Indiana	1168	1132	432	784	732	176	608
Iowa	1216	1052	352	1036	1014	306	658
Kansas	810	810	196	1052	1040	394	590
Kentucky	1280	1060	882	1152	1030	154	1036
Louisiana	720	646	496	574	552	116	612
Maine	2934	2520	664	1554	1378	200	864
Maryland	552	294	114	290	216	68	182
Massachusetts	628	492	208	378	260	66	274
Michigan	718	448	46	1302	1120	220	266
Minnesota	1230	604	112	1232	990	168	280
Mississippi	1104	978	388	1176	1104	208	596
Missouri	1894	1628	1112	1868	1678	482	1594
Montana	15,960	8816	1752	6012	4508	1586	3338
Nebraska	1042	924	162	1244	1158	546	708
Nevada	390	224	16	1738	1318	174	190
New Hampshire	1102	930	210	716	564	138	348
New Jersey	324	250	88	186	150	40	128
New Mexico	1092	608	26	2174	1664	286	312
New York	5128	3934	856	3022	2488	658	1514
North Carolina	2574	2024	398	1640	1422	300	698
North Dakota	108	106	32	260	250	48	80
Ohio	976	868	394	1080	984	244	638
Oklahoma	940	872	252	1512	1404	440	692
Oregon	23,688	13,146	2440	6078	4830	1704	4144
Pennsylvania	4888	3302	1318	2958	2134	590	1908
Rhode Island	32	28	0	36	32	14	14
South Carolina	1204	1094	306	674	612	116	422
South Dakota	252	136	46	786	768	192	238
Tennessee	2912	2314	962	1800	1598	348	1310
Texas	1216	1042	150	3182	3038	506	656
Utah	4334	3114	72	2998	2656	730	802
Vermont	1234	1128	224	876	832	210	434
Virginia	2500	2168	448	1646	1536	388	836
Washington	32,590	17,298	4526	4202	3462	1686	6212
West Virginia	4288	2920	678	1438	1354	292	970
Wisconsin	1370	1248	296	1106	1026	222	518
Wyoming	8014	3914	320	3580	2476	694	1014
Total	311,202	183,642	36,896	119,888	91,572	21,986	58,882

Source: Feasibility assessment of the water energy resources of the United States for new low power and small hydro classes of hydroelectric plants (USDOE, 2006).

conservative estimates of additional hydropower capacity available due to new generating potential at existing large dams. The total is close to 30,000 MW, or an additional 38% of current hydropower capacity in the United States.

The second column in Table 6 reduces this gross "potential" by environmental constraints, similar to the ones listed above in the discussion on uprating. If a location is considered wild or scenic, has cultural value, geologic value, historic value, or protected fish or wildlife species, then development was considered highly unlikely. The environmentally "friendly" estimate of hydropower capacity additions to existing large dams is therefore closer to 17,000 MW.

5.4. Hydrokinetics

The data on hydrokinetic potential nationwide are still very preliminary. Estimates have ranged from minimums of 23,000 MW (Bahleda and Hosko, 2007) to maximums of 400,000 MW (Bedard, 2006). Any potential power will be located primarily along the coasts, where current wave and tidal prototypes are being employed, but future hydrokinetic technologies will also take advantage of the wave power in streams and rivers. This will benefit many of the inland states. Unfortunately, there are too many current uncertainties to try and break down these power potential estimates by state.

6. Emissions saved

Table 7 brings together Tables 1–6.[20] It provides the upper ("total potential") and lower ("total friendly") bounds of potential water power available per state from all sources (minus any hydrokinetic potential). It then translates these totals into carbon

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[20] An engineer at the Idaho National Laboratory pointed out that it is possible, though by no means certain, that there could be some double counting between Tables 4 and 6.

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Table 5
US uprating potential at existing hydropower dams, by state (MW)

State	Total potential	Total friendly
Alabama	10	5
Alaska	65	58
Arizona	207	157
Arkansas	165	149
California	748	290
Colorado	156	78
Connecticut	21	11
Delaware	0	0
Florida	0	0
Georgia	141	101
Hawaii	3	3
Idaho	1,003	504
Illinois	80	41
Indiana	16	8
Iowa	115	61
Kansas	0	0
Kentucky	19	10
Louisiana	0	0
Maine	83	47
Maryland	196	20
Massachusetts	28	14
Michigan	25	17
Minnesota	98	72
Mississippi	0	0
Missouri	116	104
Montana	470	235
Nebraska	46	28
Nevada	5	4
New Hampshire	0	0
New Jersey	0	0
New Mexico	11	5
New York	286	162
North Carolina	16	14
North Dakota	86	43
Ohio	2	1
Oklahoma	274	179
Oregon	44	11
Pennsylvania	207	105
Rhode Island	0	0
South Carolina	6	3
South Dakota	569	285
Tennessee	0	0
Texas	56	46
Utah	48	8
Vermont	69	32
Virginia	16	12
Washington	1,033	875
West Virginia	0	0
Wisconsin	190	111
Wyoming	0	0
Total	6,732	3,908

Source: US Hydropower Resource Assessment Final Report (USDOE, 1998). Numbers may not match exactly due to rounding error.

Table 6
New US generating potential at existing dams, by state (MW)

State	Total potential	Total friendly
Alabama	281	216
Alaska	2866	1610
Arizona	51	15
Arkansas	378	332
California	4627	1933
Colorado	782	377
Connecticut	27	14
Delaware	0	0
Florida	49	34
Georgia	719	540
Hawaii	20	13
Idaho	541	447
Illinois	457	242
Indiana	51	34
Iowa	310	219
Kansas	53	45
Kentucky	851	425
Louisiana	78	67
Maine	1069	768
Maryland	32	10
Massachusetts	118	62
Michigan	459	354
Minnesota	73	51
Mississippi	81	62
Missouri	203	181
Montana	1129	502
Nebraska	117	62
Nevada	41	31
New Hampshire	51	25
New Jersey	6	5
New Mexico	48	24
New York	754	495
North Carolina	594	369
North Dakota	13	7
Ohio	183	138
Oklahoma	78	68
Oregon	2549	1916
Pennsylvania	310	187
Rhode Island	12	10
South Carolina	855	444
South Dakota	548	405
Tennessee	20	10
Texas	164	140
Utah	900	414
Vermont	261	130
Virginia	690	376
Washington	3541	1794
West Virginia	1597	1002
Wisconsin	53	16
Wyoming	920	487
Total	29,611	17,108

Source: US Hydropower Resource Assessment Final Report (USDOE, 1998). Numbers may not match exactly due to rounding error.

emissions saved. The conversion process employs a couple of important assumptions. First, it assumes that any additional hydropower developed would replace electricity generation from fossil fuel use. Power generators generally have a portfolio of generation assets available for supplying electricity, including coal-fired plants, gas-fired plants, petroleum-based plants, and renewables; determining exactly which plant(s) in particular would be replaced if additional water-based resources were developed is complex (Sale and Hadley, 2002). The answer depends in a heterogeneous fashion across utilities, across time, and certainly across space.[21] Rather than try to determine the exact replacement plants for every power generator in the country (a paper unto itself), we assume that any additional hydropower generated from the reserves listed in Table 7 will be in lieu of electricity generated with some form of carbon emissions. The impetus for RPS legislation nationwide is essentially to replace fossil fuel-generated electricity with electricity generated from renewables. Our estimates assume, therefore, the replacement of water power for an average of the top carbon-emitting fossil fuels (coal, natural gas, and petroleum products). This implies that our numbers will be *underestimates* if a certain region of the country relies primarily on coal-fired plants; similarly, our numbers will be *overestimates* if a certain region of the country relies on relatively less carbon-emitting gas-fired plants as their swing production plant.

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[21] Sale and Hadley (2002) find that parts of the Northeastern United States rely more on coal-fired steam plants as their swing production, while the Southwestern United States, for example, depends more on gas-fired plants.

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Table 7
Potential emissions saved from US hydropower production, by state

State	Total potential	Total friendly	Emissions potential	Emissions friendly	Emissions 2003[a]
Alabama	3671	1143	22.63	7.05	136.0
Alaska	130,307	7056	803.37	43.50	44.8
Arizona	5537	473	34.14	2.91	88.8
Arkansas	4490	1661	27.68	10.24	62.4
California	47,127	9071	290.55	55.92	388.9
Colorado	14,998	2237	92.47	13.79	89.7
Connecticut	825	234	5.08	1.44	42.4
Delaware	42	12	0.26	0.07	17.2
Florida	903	190	5.57	1.17	243.9
Georgia	4260	1101	26.26	6.79	168.0
Hawaii	3743	575	23.07	3.55	21.5
Idaho	30,722	5195	189.41	32.03	14.2
Illinois	2109	1419	13.00	8.75	230.0
Indiana	2019	650	12.45	4.01	235.1
Iowa	2677	938	16.51	5.78	78.9
Kansas	1915	635	11.80	3.92	79.9
Kentucky	3302	1471	20.36	9.07	143.0
Louisiana	1372	679	8.46	4.19	179.1
Maine	5640	1679	34.77	10.35	23.3
Maryland	1070	211	6.60	1.30	78.8
Massachusetts	1152	351	7.10	2.16	87.0
Michigan	2504	636	15.44	3.92	184.9
Minnesota	2633	403	16.23	2.48	102.4
Mississippi	2361	658	14.56	4.06	62.1
Missouri	4081	1879	25.16	11.59	137.2
Montana	23,570	4075	145.32	25.12	32.7
Nebraska	2449	798	15.10	4.92	43.2
Nevada	2174	225	13.40	1.39	43.3
New Hampshire	1869	373	11.52	2.30	20.5
New Jersey	516	133	3.18	0.82	123.7
New Mexico	3325	342	20.50	2.11	57.6
New York	9190	2171	56.66	13.38	214.3
North Carolina	4824	1081	29.74	6.67	146.2
North Dakota	468	130	2.88	0.80	50.7
Ohio	2241	777	13.82	4.79	265.5
Oklahoma	2804	938	17.29	5.78	103.3
Oregon	32,360	6071	199.50	37.43	40.4
Pennsylvania	8363	2200	51.56	13.56	271.4
Rhode Island	80	24	0.49	0.15	11.4
South Carolina	2738	870	16.88	5.36	79.2
South Dakota	2156	928	13.29	5.72	13.7
Tennessee	4732	1320	29.17	8.14	120.1
Texas	4618	841	28.47	5.19	670.2
Utah	8280	1224	51.05	7.55	62.4
Vermont	2441	596	15.05	3.67	6.5
Virginia	4852	1224	29.91	7.54	122.6
Washington	41,366	8881	255.03	54.75	78.7
West Virginia	7323	1972	45.15	12.16	114.4
Wisconsin	2719	645	16.77	3.98	104.8
Wyoming	12,514	1501	77.15	9.25	62.9
Total	467,433	79,898	2881.82	492.59	5798.9

The first two columns are measured in megawatts, and the final three columns are measured in millions of metric tons.

[a] *Source*: Energy Information Administration, State Energy Data System.

Our second important assumption is that water-based plants operate at a capacity factor of around 90%. Capacity factor is the percentage of time a generating facility is actually in use, as opposed to its total potential operating capacity. Plant factors of around 50% are sometimes assumed for the average fossil fuel-based generating plant (Sale and Hadley, 2002), but the environmentally friendly hydropower discussed in this paper is for the most part run-of-river, nearly constant, base power. Assuming factor capacities of around 90% is not anomalous.[22]

The conversion process from megawatts potential produced to emissions saved is conducted in three steps. First, megawatt capacity is translated into kilowatt hours produced.[23] Then, an estimate is made of the pounds of emissions (E) avoided per kilowatt hour of electricity generated through hydropower. The conversion equation is $E = XY$, where X is the average carbon dioxide emission factor for coal, natural gas, and oil (per Btu), and Y is the heat rate conversion factor of Btu per kilowatt hour.[24] The final value for E used in Table 7 is $E = 1.724$ pounds of emissions per kWh. Finally, E is multiplied by the measure of kilowatt hours produced, and then converted to metric tons to produce the two

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[22] This was confirmed in a July 2007 telephone conversation with hydropower experts employed by the DOE's Idaho National Laboratory.

[23] 1 MW = 8,760,000 kWh of energy.

[24] These source data for estimates of X and Y come from the Energy Information Administration's website and its "Annual Energy Review 2001," Appendix A and C.

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Table 8
Friendly US hydropower production in comparison to RPS goals

State	Total friendly	State RPS	Federal RPS
Alabama	1143	–	1553
Alaska	7056	–	106
Arizona	473	1254	1254
Arkansas	1661	–	799
California	9071	6004	4503
Colorado	2237	1135	852
Connecticut	234	976	542
Delaware	12	264	198
Florida	190	–	3908
Georgia	1101	–	2309
Hawaii	575	241	181
Idaho	5195	–	390
Illinois	1419	4065	2439
Indiana	650	–	1809
Iowa	938	105	742
Kansas	635	–	681
Kentucky	1471	–	1520
Louisiana	679	–	1327
Maine	1679	421	210
Maryland	211	685	1082
Massachusetts	351	319	956
Michigan	636	–	1850
Minnesota	403	1906	1143
Mississippi	658	–	804
Missouri	1879	1030	1404
Montana	4075	237	237
Nebraska	798	–	467
Nevada	225	790	592
New Hampshire	373	317	190
New Jersey	133	2047	1364
New Mexico	342	489	367
New York	2171	4059	2436
North Carolina	1081	1808	2170
North Dakota	130	–	193
Ohio	777	–	2627
Oklahoma	938	–	940
Oregon	6071	1372	823
Pennsylvania	2200	3087	2503
Rhode Island	24	36	134
South Carolina	870	–	1385
South Dakota	928	–	172
Tennessee	1320	–	1780
Texas	841	10,000	5869
Utah	1224	–	451
Vermont	596	46	99
Virginia	1224	1462	1827
Washington	8881	1456	1456
West Virginia	1972	–	553
Wisconsin	645	797	1196
Wyoming	1501	–	256
Total	79,898	46,406	62,646

Measurements are in megawatts (MW).

emissions avoided column estimates, "emissions potential" and "emissions friendly". The final column in Table 7 gives actual 2003 emissions data from each state, as a comparison against the potential emissions avoided as a result of increased hydropower production. If all environmentally friendly hydropower resources were developed (our conservative *lower* bound), this would result in an 8.5% reduction in total US carbon emissions.[25] That is significant. Some states have an ability to reduce emissions levels beyond what they even produce (for example Alaska, Idaho, Montana, Oregon, and Washington), so the 8.5% figure is only possible if electricity supply is fully transferable across state borders, which is somewhat unrealistic. In practice, this means that the 8.5% estimate is high. However, as a forward-looking goal, this number provides initial evidence that gains in reducing greenhouse gas emissions can be achieved if additional hydropower development is pursued. These gains can also be achieved in an environmentally friendly fashion, and in just a few years; unlike many other renewables, the technology for hydropower development is firmly established.[26]

Finally, Table 8 compares total friendly electricity production from water power with RPS goals across the country. As of 2007, only 28 states had enacted some form of RPS legislation, and the goals for each are quite heterogeneous; some states require that RPS apply only to public utilities, others that they apply only to particular private utilities. Some RPS ramp up in degree over time, others do not. A few (in particular, Massachusetts) even make a point of excluding new hydropower production as a viable renewable. What all these RPS do have in common is that they are still very fresh and implementation is uncertain. Some RPS goals, in fact, are actually voluntary, as in Missouri and Virginia. The second column in Table 8 provides estimates of the maximum electricity supply required to be produced from renewables to achieve state-level RPS goals, applied to 2006 levels of electricity consumption. Many states can achieve over 50% of these goals with additional environmentally friendly hydropower production alone, including California, Colorado, Hawaii, Iowa, Maine, Massachusetts, Missouri, Montana, New Hampshire, New Mexico, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Virginia, Washington, and Wisconsin. The final column in Table 8 provides the renewable electricity supply that would be required if Congress passed a federal-level RPS goal of 15%. Thirty-four states would be able to achieve more than 50% of this goal with additional friendly hydropower production alone.

7. Benefit–cost considerations

Clearly, environmentally friendly hydropower production has the potential to contribute to a solution for reducing climate change. What has been left out of the discussion so far, however, is a more thorough comparison of all of the benefits, and costs, of increased hydropower production. Efficiency demands a look, not just at the benefits of any new renewable energy resources, but at the cost of their development as well. If development costs turned out to be many times the cost of photovoltaic cells, for example, it would be a waste of resources to produce even environmentally friendly hydropower production, despite the reductions in carbon dioxide emissions levels it would imply (as these same reductions could be achieved elsewhere, and more cheaply).

Table 9 presents a list of the main categories of costs and benefits for all types of new water power production discussed in this paper. Quantitatively measuring each of these items, for each resource, is beyond the scope of this paper. Instead, we present a more qualitative discussion of each of these items to give the reader a general feel for their relative importance.

7.1. Benefits

All of the hydropower resources considered in this paper have the following four categories of associated benefits: electricity production, carbon dioxide emissions avoidance, decentralization of power resources, and reliability and flexibility of power

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[25] If all potential hydropower resources were developed (our current upper bound), this would reduce US carbon emissions by 50%.

[26] The regulatory and licensing requirements surrounding practical development of any water-related electrical facility can, however, delay implementation for up to several years.

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Table 9
Benefits and costs of increased hydropower production

	Benefits	Costs
Small/micro	Electricity production Carbon dioxide emissions avoidance Decentralization of power resources Reliability/flexibility of power resources Recreational benefits Irrigation benefits	Licensing and regulatory costs Construction costs Operating and maintenance costs Negative riverine effects
Uprating	Electricity production Carbon dioxide emissions avoidance Decentralization of power resources Reliability/flexibility of power resources Flood control Navigation benefits Recreational benefits Irrigation benefits	Licensing and regulatory costs Construction costs Operating and maintenance costs Negative riverine effects
Existing dam development	Electricity production Carbon dioxide emissions avoidance Decentralization of power resources Reliability/flexibility of power resources Flood control Navigation benefits Recreational benefits Irrigation benefits	Licensing and regulatory costs Construction costs Operating and maintenance costs Negative riverine effects
Hydrokinetics	Electricity production Carbon dioxide emissions avoidance Decentralization of power resources Reliability/flexibility of power resources	Licensing and regulatory costs Construction costs Operating and maintenance costs Negative oceanic effects

resources. As a group these benefits have significant value. First, electricity production is fundamental in maintaining a growing economy. Demand for electricity is unlikely to diminish anytime soon, and power companies are currently scrambling to find ways to enhance supply. As the market prices for fossil fuels, the main alternatives to source production for electricity, increase, the value of the electricity produced from hydro resources also increases. In 2007 the average retail price of electricity across the United States, to all sectors, was 9.44 cents per kWh. Applying this figure to the total friendly hydro capacity documented in Table 7 gives an approximate value to the annual electricity produced of $66 billion.[27]

The carbon dioxide emissions avoided from increased hydro production can also be roughly estimated. Carbon dioxide exchanges (such as the Chicago Climate Exchange and the EU Emission Trading Scheme) have produced highly variable rates for carbon dioxide emissions credits, from less than $1.00 per ton of carbon dioxide emissions avoided, to over $50.00 per ton.[28] In the United States, ‘‘Green Tags’’ produced by the Bonneville Environmental Foundation and sold to individuals to offset their personal carbon emissions offer electricity offset prices ranging from $20 (for wind green tags) to $56 (for solar green tags). If we assume a middle value for carbon dioxide emissions reductions of $30 per ton, the friendly emissions reduction potential documented in Table 7 has a market value of $20.6 billion.[29]

Valuing the decentralization of power resources across the country is trickier, because it requires estimating a market value for something that is not sold in a traditional exchange. The decentralization of power resources has value because it makes the US less dependent on the vicissitudes of foreign governments for fossil fuel supplies, because decentralized power resources are more reliable (if a few small hydro plants go offline, this in unlikely to lead to mass power outages), and because geographically dispersed resources are less vulnerable to system-wide disturbance or attack.[30] In essence, decentralized power resources have significant positive national security and reliability externalities, but putting a numerical value on this benefit is theoretically difficult (Mignone, 2007; Greene and Leiby, 2006).

Finally, hydropower is known for its flexibility in smoothing supply in the overall electricity industry (recall Fig. 2). Because hydroelectric power can be generated within minutes, and most other forms of electricity production have start-up lags of half an hour or more, hydropower production is extremely important for taming spikes in spot electricity prices (Kosnik, 2008). This function applies primarily to the larger hydro facilities, but even smaller facilities that generate power continuously can easily direct that power from a battery backup, straight to the grid. Hocker (1992) has found that many utility companies value their hydropower resources at least as much for their reserve benefits, as for the raw power that they produce.[31] Recent sales of hydropower generating assets have found that their final sale prices have come out above their book value, implying a premium

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[27] This 79,898 MW of total friendly hydro capacity is equivalent to 1.2 billion barrels of oil, or 433.6 million tons of coal (conversion statistics from Warner (1993)).

[28] The Congressional Budget Office, in a 2003 technical report, found that permit prices under the Kyoto Protocol could range from $56 per metric ton of carbon to $178 per metric ton in 2010 (Lasky, 2003).

[29] This is equivalent to removing 52.8 million passenger cars from the roads, where a ‘‘car equivalent’’ in emissions reductions is calculated from the emissions of a typical passenger car traveling 12,000 miles in a year at an average fuel efficiency of 22 mpg (Sale and Hadley, 2002).

[30] In emergencies, hydropower can even come to the rescue. Hydro plants in New York and elsewhere had a noted role in the North American blackout of 2003, stabilizing the grid and restoring power to 50 million people in the largest blackout in US history (NHA: Blackout Study Highlights Hydro’s Role, 2004).

[31] The Hocker (1992) article focuses on pumped-storage hydropower plants, but the flexibility qualities of hydropower are applicable to non-pumped-storage plants as well (Hirst, 2005).

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for hydropower-specific generating assets that is likely attributable to these reliability and flexibility benefits (Hydro Currents, 1999).

The other hydropower benefits mentioned for some types of hydropower sources, including flood control, navigation benefits, recreational benefits, and irrigation benefits, are site specific and likely to be minor relative to the previous categories of benefits mentioned. Large hydropower facilities are often cited as having many of these extra benefits, but uprating and new development at existing dams will likely not *add* anything to what is already being produced. And while small and micro hydropower facilities, by creating access points to rivers, may marginally increase the ability to simultaneously use these resources for recreation and irrigation purposes, the total benefits are likely to be small. Hydrokinetic facilities, meanwhile, have none of these additional miscellaneous benefits.

In sum, if the pantheon of benefits to additional hydropower resource development were quantitatively estimated, the value would likely increase hydropower's current market value by at least 50%.[32]

7.2. Costs

Every form of hydropower production discussed in this report is subject to some form of regulatory oversight, either by FERC, or from state and local environmental quality boards. The costs of licensing and compliance with regulatory oversight can vary for each project, from next to nothing for small sites exempted from federal-level oversight, to many millions of dollars, generally for larger facilities (Kosnik, 2006). There is a growing awareness that these costs may be retarding development of some important renewable resources (Perspectives on Hydropower: Federal Organizations Share Views, 2003), and so, in part spurred on by provisions in the 2005 Energy Bill, regulatory agencies (including FERC) are currently investigating reform of the oversight procedures associated with the additions to hydropower capacity described in this report. At the moment, however, licensing and regulatory costs related to the additional development of hydropower capacity have the potential to be significant (Kamberg, 2005).

The construction costs associated with additional hydroelectric capacity vary by type. Building new small and micro hydro facilities is an extremely site-specific endeavor. Most experts estimate that only 25% of the costs of a small or micro hydro facility can be determined in a general way from fixed costs; over 75% of the total costs depend on location and site conditions.[33] Sample facilities that have already been constructed produced installation cost estimates that ranged from $2100 to $15,000 (Davis, 2003). The most that can be said in a general way is that some small and micro hydro facilities will have relatively low construction costs, while others will not. The environmentally "friendly" hydropower capacity numbers used in Table 4 imply costs on the lower end of the scale, as these numbers were produced from facilities constrained to be developmentally feasible, including proximity to roads and existing transmission lines.

The construction costs associated with uprating capacity potential vary by whether the efficiency improvements come from simple measures (such as switching from error-prone manual, to more accurate computer controls, of gates, switches, and monitoring equipment), or from something more complicated, like full turbine replacement. In the first instance, additional capacity can be gained at as low as half the cost of new hydro capacity (O'Connor, 1993); in the second instance, installing the newest, most efficient large hydroelectric turbines can cost many hundreds of thousands of dollars.

Estimates of the construction costs associated with installing hydroelectric capacity at currently existing dams are hard to find. This is likely because, as with small and micro hydro facilities, the installation costs vary according to specific site characteristics. Final costs will also depend on the size of the capacity additions to be made. Bahleda and Hosko (2007) provide an example of power developed by private investment at a federal facility, where the cost came to a reasonable $1500 per kW of capacity; one would assume that such additions are possible in other instances in a similarly cost-effective fashion.

The construction costs of hydrokinetic facilities are currently very high. This is because hydrokinetic electric power is still in the development stage, and the large turbines, buoys, and other necessary mechanical equipment are still experimental prototypes. Many companies investing in hydrokinetic facilities currently receive large parts of their funding from government grants and foundational support. In the future, once the technology has been developed and refined, installation costs of hydrokinetic facilities are expected to diminish and to become as cost-effective as traditional hydroelectric plants. At the moment, however, this is only speculation.

The operation and maintenance (O&M) expenses for all of the hydropower sources cited in this report are minimal. Small and micro hydro facilities have operational lives of over 50 years and the only maintenance required is periodic cleaning of the intake facilities (to free them from brush and other river debris) and the occasional belt or gear replacement. Uprating certainly requires no new O&M costs beyond what is already being incurred to run the original facility—if anything, these costs can even decline if some of the efficiency improvements lead to a tighter run operation. Existing dam development also has minimal operating and maintenance costs, as with any hydroelectric power facility. Finally, hydrokinetic power plants are also expected to have long lives and, as with traditional hydroelectric power, minimal periodic O&M costs.

The negative riverine and oceanic effects of the hydropower sources under discussion are also minimal. The entire point of the "friendly" hydroelectric capacity numbers produced by the DOE, and utilized in this report, was to report only that potential with minimal to zero negative riverine impacts. Small and micro hydropower facilities have such a small footprint because they are able to leave significant water resources in-stream to maintain riverine integrity. Hydrokinetics has been criticized for a possible "cuisinart" effect, whereby turbines in the ocean attract fish life and kill and chop them up. This will likely happen to some degree, but it is doubtful that it will happen to any sort of a significant degree.[34] An analogy can be made to the effect of wind turbines on birds. Some birds do indeed fly in the way of wind turbines and are maimed or killed in the process, but not enough to significantly effect any known avian species.

In summary then, the largest, and most significant, unknown in relation to costs are the licensing and construction costs, for each type of hydropower technology discussed. A worthwhile future research agenda would be an attempt at a more in-depth

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[32] This implies a ball-park estimate for the positive externalities of reliability and flexibility of at least an additional 20% of the market value of the electricity currently produced.

[33] Important cost-determining parameters include ground soil type, head versus flow ratio, the length of penstock required, if the penstock must be winterized and buried, and the length and type of transmission line required.

[34] A prototype in New York (RITE—The Roosevelt Island Tidal Energy project) estimated the probability of fish being injured be their rotating turbine blades at only 0.004–0.457%.

analysis of the heterogeneous construction costs, per site. Until that is done, we really cannot know how costly development of these resources would be. However, it is unlikely that the development costs, for every available site, would be more than 50% the current development costs of hydroelectric power. From our earlier analysis of the benefits of increased hydropower capacity, we roughly determined that the total, including all positive externalities, likely increases the current market value of hydropower by at least 50%. Therefore, costs can also be increased by at least 50% of a conventional facility while still maintaining social cost-effectiveness. In addition, as climate change concerns grow, and as fossil fuel prices maintain their upward trends, whatever the ultimate costs of increased hydropower capacity are, they are becoming most cost-effective by the day.

8. Conclusion

This paper has reviewed the role that water-based electric power generation can play in reducing the greenhouse gas emissions that lead to climate change. Ranges of estimates of potential developable new electrical capacity were produced, in particular, for electricity coming from small/micro hydropower facilities, from uprating at existing hydropower facilities, and from installing new facilities at existing non-hydropower dams. These estimates were then turned into potential emissions saved if the facilities documented were actually developed, as well as the ability of this capacity to satisfy RPS goals across the country.

Many assumptions had to be employed to come up with the numbers documented in this report, some of which imply the numbers are underestimates (for example, not including municipal conduit potentials to the numbers for new facilities at existing dams, as well as not attempting to measure the potential from hydrokinetics whatsoever); others of which imply the numbers may be high (for example, capacity factor assumptions and swing electricity production deriving from a non-weighted average of all fossil fuel plants). Additional research refining these assumptions would certainly be beneficial in aiding our understanding of exactly how much, and to what degree, the various forms of water power can contribute to a solution to climate change.[35] As a preliminary estimate, however, the results presented in this paper clearly show that hydropower can play a significant role in reducing US carbon emissions, anywhere from 8.5% to 50% of 2003 emissions levels, and satisfying as much as 50% of current RPS goals for 18 states in the country.[36] Recent polls have found that the great majority (84–90%) of US citizens have rather positive opinions of hydroelectric power (Restructuring and Regulation: Seeking the Rewards and Avoiding the Perils, 1999).[37] Hydropower's social benefits also extend beyond those discussed in this paper, including the avoided production of additional harmful emission types, including sulfur dioxide, carbon monoxide, particulate matter, volatile organic compounds, lead, methane, and others.

Currently, the primary practical constraint to developing many of these documented water-based resources appears to be a complex regulatory environment. After nuclear power, hydropower is the most regulated of any electrical energy source (Kosnik, 2008; Barnes and Byers, 1997). Water resource development sites generally have to gain approval not just from the federal government (through FERC), but also often from state and local environmental and water quality boards. This can be a time-consuming, expensive, not to mention repetitive process. For some facilities, this process can be beneficial in airing out the potential consequences of developing a particular water power site, adding legitimacy to the political process of approving new electrical resources. But for other facilities, it is enormously inefficient (Kamberg, 2005; Barnes, 1993). There is a growing consensus that the regulatory environment surrounding water power development, historically formulated from experiences with large, traditional hydropower dams, needs to be reformulated to address the contemporary, unique circumstances of small/micro hydropower plants and the newer forms of water power development such as hydrokinetics and uprating.

Hydropower will never be the complete answer to the problem of carbon emissions and global climate change; even at its utmost potential it cannot eliminate all our carbon emissions or satisfy 100% of the various state RPS goals. But the technology exists now, and in a more mature form than any other source of renewable energy. This paper documents that the resources to implement more of it, and in an environmentally friendly manner, are also widespread and diversified. The social benefits to increased hydropower production are too many not to give the power of water greater attention as we seek to both maintain electricity supplies, and reduce our impact on the global environment.

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[35] Current research on hydropower, relative to research on other forms of renewable energy, is astoundingly small. For example, the federal government in 2004 approved $343 million for renewable energy research. Of that, only $5 million (1%) went to hydropower, and even this small amount was completely eliminated in 2005 (effective FY2007).

[36] This implies that ruling out new hydro in RPS statutes (as one state has already indeed done) is not necessarily environmentally beneficial, particularly if these statutes rule out *all* new hydro, including the environmentally friendly types described in this paper.

[37] As do Europeans, Canadians, and many other peoples in the rest of the world.

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