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The potential for small scale hydropower development in the US

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ABSTRACT

In an earlier paper (Kosnik, 2008), the potential for small scale hydropower to contribute to US renewable energy supplies, as well as reduce current carbon emissions, was investigated. It was discovered that thousands of viable sites capable of producing significant amounts of hydroelectric power were available throughout the United States. The primary objective of this paper is to determine the cost-effectiveness of developing these small scale hydropower sites. Just because a site has the necessary topographical features to allow small scale hydropower development, does not mean that it should be pursued from a cost-benefit perspective, even if it is a renewable energy resource with minimal effects on the environment. This analysis finds that while the average cost of developing small scale hydropower is relatively high, there still remain hundreds of sites on the low end of the cost scale that are cost-effective to develop right now.

1. Introduction

In the last decade, as concerns over global climate change have multiplied and criticisms over traditional fossil fuel based energy supplies have grown, interest in developing domestic renewable energy supplies has increased. Billions of dollars in research money and many hours of scientific effort have been spent analyzing everything from algaeoleum to geothermal heating. As of yet, however, no single technology has proven itself to be the panacea to the nation's energy problems, and so, efforts continue along a panoply of renewable energy fronts. Complementary to these trends, the number of states that have passed Renewable Portfolio Standard (RPS) legislation, or legislation that puts percentage-based renewable energy production requirements on electricity loads, has increased exponentially in recent years. In 2003 only three states in the US had passed RPS legislation, but by 2008 the number had grown to 34.[1] In March 2009, Congress again tried to get into the game, introducing The American Clean Energy and Security Act of 2009, which seeks to implement a federal-level RPS at 25% of electricity supply by 2025. This paper focuses on the potential for development of one specific type of renewable power resource in the US, small scale hydropower.

Small scale hydropower is distinct from traditional hydropower in that it is defined by generation capacities of 30 MW or less, per site. This is important because such small generation facilities have very few of the negative riverine impacts to which larger, more conventional hydropower plants have been prone to.[2] As the main criticism of conventional hydropower development has been the local impact on fishery resources and riverine ecosystems, small scale hydropower presents an alternative, win–win situation: no carbon emissions *and* a negligible local environmental footprint. In the following paper we explore the possibility of developing small scale hydropower in the US. We discuss the list of potential sites, the cost of developing these sites, and the range of benefits small hydropower production would imply.

In 2004, the Department of Energy (USDOE, 2004) analyzed every two-mile stream segment in the United States for its potential as a hydropower development site. This database identified nearly 500,000 viable small scale hydropower sites, capable of providing more than 100,000 MW of power.[3] This represents approximately 10% of current electric generation capacity in the US, and 80% of current renewable generation supplies (EIA, 2009). Such an amount is clearly not enough to eliminate fossil fuel usage in the United States, however, it is enough to satisfy many RPS strictures beyond 2020. States in the Pacific Northwest, including California, Washington, Idaho, and Oregon, contain the majority of the small scale hydropower potential, but there is not a single state in the nation that does not

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[1] Four of these legislative RPSs, however, are comprised of voluntary rather than mandatory renewable energy production goals.

[2] The Low Impact Hydropower Institute, a nonprofit organization that certifies hydropower facilities as environmentally friendly, points out that size is not the only determinant for gauging a site's environmental impact (Grimm, 2002). Mode of operation and age, for example, also matters. Size, however, does serve as a reasonable proxy for the facility's local environmental footprint.

[3] In fact, the database identified sites capable of providing nearly 300,000 MW of power in total, but that gross number includes large hydropower sites, sites that have already been developed, as well as sites that are federally excluded from any kind of development.

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have the ability to benefit at least somewhat from additional small scale hydropower development. In addition, hydroelectric power generation – having first been developed over one hundred years ago – is a mature technology, unlike most other renewables. There already exist competitive companies that produce turbines and other equipment necessary to develop most small scale hydropower potential, and, this equipment is sturdy and reliable, with turbine life spans lasting many decades. The raw materials used to develop small scale hydropower sites are also conventional and readily available, implying that input prices would be unlikely to spike if production were increased, as has repeatedly occurred with the silicon necessary for solar power production, for example (Prometheus Institute, 2006).

The primary objective in this paper is to determine the cost-effectiveness of developing these small scale hydropower sites. Just because a site has the necessary topographical features to allow small scale hydropower development does not mean that it should be pursued from a cost-effectiveness perspective. If the costs of development turned out to be prohibitive, this would tell us that we should direct our efforts at developing solar, wind, or some other renewable power source instead. If, instead, the costs turned out to be relatively small, this would imply that a wise policy choice would be to make a concerted effort to develop these documented small scale hydropower sites. In order to determine the costs of developing these small scale hydropower sites, key site characteristic variables were input into various costing programs to achieve rough estimates.

The first result is that small scale hydropower construction involves nonlinear economies of scale. We divide small scale hydropower plants into three distinct power (P) classifications: "small" (where $30\text{ MW} \geq P \geq 1\text{ MW}$), "mini" (where $1\text{ MW} > P > 100\text{ kW}$), and "micro" (where $100\text{ kW} \geq P$).[4] By doing this we find that, while there are individually cost-effective sites available for development in each of these categories, "small" hydropower sites are significantly more cost effective on average than either "mini" or "micro" sites. Essentially, the really tiny sites, those that could only produce enough power for a single household, or perhaps a single block, are, at current technologies and with current equipment prices, for the most part best left undeveloped.[5]

The second result is that the average cost to develop a "small" hydropower site is around $5,000 per kW. This is high; to be cost-competitive with fossil fuels, current estimates are that renewables need to be closer to $2,000 per kW. However, $5,000/kW is an average figure; there are still hundreds of small hydropower sites on the lower end of this scale, which can be developed for $2,000/kW or less. This implies that there is some small scale hydropower potential that is cost-effective right now. As worries about climate change increase, finding the potential to reduce even some greenhouse gas emissions, cost-effectively and quickly, has value.

The results from our analysis also show us which small scale hydropower sites will become more cost-effective, if and when the United States begins pricing carbon emissions (either through a carbon tax, or, through a tradable emissions permit scheme as has been proposed in The American Clean Energy and Security Act of 2009). The greenhouse gas emissions reduction benefit of hydropower can be calculated through a simple formula, $E=XY$, where E=emissions avoided per kWh from not burning fossil fuels, X=average carbon dioxide emission factor for fossil fuels (per Btu), and Y=the heat rate conversion factor of Btu per kWh.[6] Assuming a value for carbon dioxide emissions reductions of $30 per ton, the annual emissions reduction benefit of a 10 MW small hydropower plant is $1,850,000.[7]

In fact, small scale hydropower has numerous benefits besides just electrical energy produced and carbon emissions reduced. Small scale hydropower produces no air pollutants whatsoever (including sulfur dioxide, ozone, nitrogen dioxide, and lead), it is a constant power supply source with the ability to smooth variations in supply from other, more intermittent, generation sources,[8] and it is a decentralized energy resource with national security benefits due to its entirely domestic nature.[9] If all of these ancillary benefits were also given a per MW value (as ongoing research seeks to do), the cost-effectiveness of even more small hydropower sites would rise.

In sum, this research has identified a number of small scale hydropower sites in the US that could be quickly, and cost-effectively developed.[10] Further, it has identified additional small scale hydropower sites that could be developed as circumstances evolve and renewable power resources gain in value. Small scale hydropower will never be the solution to the United States' energy needs (there is simply not enough of it available), however, this research provides evidence that it can be a useful part of a portfolio of energy solutions that satisfies both rising energy demand and calls to reduce climate change. Best of all, the technology and input materials to develop these small hydropower sites are readily available. Work on building them could begin right away (subject to regulatory approval), addressing calls to reduce carbon emissions in the near term.[11]

The remainder of this paper is structured as follows: Section 2 describes the mechanics of small scale hydropower production, Section 3 details the data used in the analyses, Section 4 offers an explanation of the three different costing algorithms utilized, Section 5 reports the empirical results, and Section 6 summarizes and concludes.

2. The mechanics of small scale hydropower

A small scale hydropower facility generates power through the kinetic energy of moving water as it passes through a turbine. Most small scale hydropower facilities are "run-of-river," meaning that the natural flow of the river is maintained, and that a dammed reservoir is not created in order to generate power.[12] Without a permanent dam to block river flow, nor a large

[4] Division of hydropower sites into power classification categories is common in the literature, however, the names given to each division are not standardized (some publications use the term "pico" instead of "micro," for example, or do not distinguish the "mini" categorization at all), nor are the exact power classification boundaries.

[5] Except, perhaps, by the back-door enthusiast whose opportunity cost of time may be low enough to make development of some of these smallest of sites still cost-effective.

[6] More details regarding this derivation can be found in Kosnik (2008).

[7] The American Clean Energy and Security Act of 2009 includes an offset provision for complying with the cap-and-trade portion of the legislation. 50% of those offsets, however, are stipulated to come from domestic sources, such as small scale hydropower. If this bill becomes law, therefore, this $1,850,000 figure becomes very pertinent.

[8] Many researchers have argued that wind and solar power are only practically viable when matched with more stable power sources, such as hydropower facilities, in order to smooth generation supplies and provide stability to the transmission grid (Benitez et al., 2008; USDOI, 2005). An anonymous reviewer adds that this load smoothing benefit of hydropower is valuable not just in conjunction with other renewables, but in and of itself as a real-time balancing resource for the grid.

[9] A few papers which discuss this national security benefit include Greene and Leiby (2006) and Mignone (2007).

[10] Although how quickly depends on the heterogeneous regulatory approval process, per state (Kosnik, 2010a, in press).

[11] Development of these sites would also provide local stimulus to struggling economies.

[12] A dam of course *could* be used to generate power, even at a small scale hydropower facility, but we purposefully obviate this possibility in our dataset in order to analyze only the most environmentally benign sites.

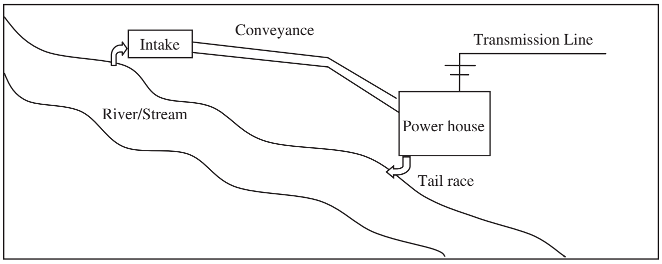


Fig. 1

reservoir to flood arable land and disrupt river temperature and composition levels, many of the negative riverine effects of traditional hydropower are avoided with a small scale hydropower plant. Fig. 1 above illustrates a typical small scale hydropower facility.

Power is produced as water runs through the system, and the amount of power produced is proportional to the vertical drop of the water flow (also known as the "head") and the water flow rate (or "flow"). The general formula for power produced is

$$P=\alpha HQ \tag{1}$$

where P=mechanical power produced, α=efficiency, density, and gravity parameters,[13] H=head, Q=flow.

Water flow through the system begins at the intake. The intake is important because it serves as the transition point from the variable stream flow of the river, to the controlled water delivery system required in order to generate power. The intake is also generally outfitted with trashracks, or debris collectors, so that it serves an important cleansing function both for the hydropower facility, as well as for the river itself. Intake of water flow is done with a weir, a low diversion structure that is built along the streambed in order to divert a portion of the river flow into a conveyance system. Weir design is very flexible; a weir can be constructed perpendicular, angular, or lateral to the river's axis (ESHA, 2004). It can be fixed, mobile, or even an inflatable structure (which is particularly good for low head sites). The key is that, with a little bit of effort, weirs can be designed to minimize local riverine impacts, while also successfully diverting a portion of river flow in order to generate hydroelectric power.

The conveyance of the water flow from the intake to the powerhouse is accomplished with a pipe, or penstock. Penstocks can be long or short (length, of course, affecting costs), they can be above ground or buried (in particular, in colder climates), and they come in a variety of materials and sizes. They, too, exist with a degree of flexibility that can be managed to maximize power production and minimize costs and environmental impact.

The powerhouse is where the activity is at. It is in the powerhouse that the flowing water turns a shaft, which drives an electric generator. The electricity then produced is directed to a transmission line for ultimate consumption. A hydroelectric turbine is what translates this flowing water into electricity produced and selection of turbine type is key—both to power production goals and cost minimization efforts. A number of parameters are considered when choosing a turbine, but by far the main one is head.[14] Recall from Eq. (1) that high head sites (a large H) require less water (Q) for a given amount of power (P). This means that the equipment necessary to produce a given amount of power at high head sites is generally smaller, and less costly, than that required at low head sites. High head sites are almost always cost effective, therefore, while very low head sites often are not. This sensitivity to H turns out to be one of the most important factors in our cost analysis below.

Finally, once the water has run through the powerhouse it is returned to the river through a tailrace. A tailrace is simply a path back to the main stem of the river. It can be long or short, wide or deep, and as simple as a dredged out channel, or as developed as a concrete lined tunnel.

Given the many components of a small scale hydroelectric facility, which all come together dependent on a variety of parameters, calculating the costs of developing any particular site is difficult. Conventional wisdom has it that only 25% of the construction costs of any small scale hydropower site can be estimated in a generic fashion based on industry-wide aggregates, and as much as 75% of the costs are dependent upon site-specific local parameters (MNRC, 2004; Davis, 2003). This is why average cost information on small scale hydropower development is not necessarily helpful for coming up with reasonably accurate cost estimates of a broad range of particular small scale hydropower sites. More detailed programming techniques are required that utilize site-specific, local parameters.

3. Data

Perhaps the most important site-specific parameters in developing the cost estimates of any particular site are P, H, and Q, or estimates of potential power available, head, and flow. In 2004 the Department of Energy (DOE) created a dataset comprised of this information for every possible hydropower development site in the US (USDOE, 2004). The dataset involved over half a million observations and included conventional (i.e. large scale) hydropower sites as well as small scale hydropower sites. It also included sites that have already been developed and sites that could not currently be developed due to federal exclusion zones (such as national parks, monuments, and wildlife refuges) or other environmental sensitivities (such as national forests or areas with legally recognized conservation easements). It was, therefore, a broad hydropower potential dataset.

In 2006 (USDOE, 2006) the DOE pared down the initial 2004 dataset in order to indentify only small scale hydropower facilities, that were also developmentally "feasible." Feasibility depended upon three factors: site accessibility, transmission and load proximity, and land use sensitivities. Site accessibility was defined as the site existing within one mile of a road. Transmission and load proximity was defined as the site existing within one mile of part of the power infrastructure (power plant, power line, or substation), or, within a reasonable distance from a populated area.[15] And land use sensitivities meant, first, that federally excluded and environmentally sensitive areas were eliminated from the dataset. It also meant that only run-of-river sites were considered, that realistic penstock lengths were considered, and that maximums of 50% or less of the instream-flow of any river body could be considered for power generation purposes. All together these criteria led to a pared down dataset that was realistic for development purposes, environmentally sensitive to local impacts, and rather conservative in power generation potential.

The DOE also extended this 2006 dataset to include additional site-specific informational parameters such as penstock length per site, nearest road to site, nearest electricity substation to site,

[13] Officially, α is a composite of the efficiency of the turbine (η), the density of the water (ρ), and the acceleration due to gravity (g) (Paish, 2002).

[14] Others include flexibility (whether the turbine will be expected to produce power under reduced flow conditions), and running speed (as the turbine matches up with the generator).

[15] For more detailed definitions on how this, and other criteria, were calculated, see USDOE (2006).

Table 1
Base data summary statistics[a].

	Min	Max	Mean	St. Deviation
Power (MW)	0.01	30.00	0.23	1.18
Head (m)	0.00	2,923.70	69.38	132.31
Flow (m^3/s)	0.01	7,520.73	25.84	190.54
Nearest road (km)	0.00	1.61	0.33	0.33
Penstock length (m)	14.18	4402.23	1029.61	897.62
Nearest powerline(km)	0.00	50.00	11.26	14.57
Nearest substation (km)	0.06	50.00	19.47	16.80
Nearest plant (km)	0.01	50.00	22.32	16.53
Nearest railroad (km)	0.00	50.00	14.74	17.31
Nearest population (km)	0.00	50.00	5.20	4.68
# of frost days at site	0.00	267.00	111.35	63.69
Small hydro	0.00	1.00	0.04	0.20
Mini hydro	0.00	1.00	0.22	0.42
Microhydro	0.00	1.00	0.73	0.44

[a] The variables listed in this table constitute the base data used in all three costing programs; actual values used in any given program were at times based on numeric manipulations of the above variables, depending on the circumstances.

nearest population center to site, and more. Each observation was also listed along with identifying county and state information, which we then used to extend the database further, adding climate and weather parameters based on NASA surface meteorology.[16]

The final composite dataset included over 125,000 observations (and approximately 30,000 MW of generation potential) and implied small scale, feasible, environmentally friendly hydropower development potential in every region of the country. It is this dataset that we analyze below for cost-effectiveness. Summary statistics are provided in Table 1.

4. Cost estimation

In the US today only 7% of total electricity produced derives from hydropower. This is likely one of the reasons why hydro receives an almost negligible portion of current research funding dollars.[17] This is unfortunate because it means that the DOE, despite recognizing a need to produce cost estimating tools for their hydropower potential datasets, has been unable so far to do so (USDOE, 2006).[18] There are a number of other countries, however, where hydropower constitutes a much larger share of electricity produced.[19] These countries, generally through government funding dollars, have developed small hydropower costing programs, or guidelines, that we have adapted in order to estimate the development potential of the small hydropower sites listed in the US.

The first costing program utilized, RETScreen International (RI), comes from the Natural Resources Department of Canada. RI is a

Table 2
RETScreen International—summary results (per kw).

"Small" hydro 30 MW ≥ *P* ≥ 1 MW	"Mini" hydro 1 MW > *P* > 100 kW	"Micro" hydro 100 kW ≥ *P*
n=5427 Min=$638 Max=$1,243,745 Mean=$8332 Median=$4989	*n*=28,616 Min=$1366 Max=$6,103,161 Mean=$18,155 Median=$11,637	*n*=1691 Min=$3939 Max=$267,250 Mean=$59,528 Median=$49,015

software package with the ability to evaluate many kinds of renewable energy projects, including solar, wind, geothermal, and hydropower. We accessed a copy of RI, Version 4, and focused on the Hydro Formula Costing Method.[20] The parameters we input for every observation in our dataset included: power potential, head, flow, number of frost days at site, turbine type, road construction length, penstock length, transmission line length, grid connection type, and voltage. There were also a few parameters which we estimated as lower and upper bounds, for example difficulty of terrain (on a 1–6 scale), and rock at dam site (yes or no).[21] From this information the program itself determined such things as turbine runner diameter, penstock thickness, and hydraulic efficiency losses. Ultimately, a final construction cost estimate was produced, which we report below.

The second costing program utilized comes from the Water Resources and Energy Directorate of Norway. Since 1980 they have developed, and regularly updated, cost estimation manuals for construction of small scale hydropower schemes. They have also written an Excel-based macro that utilizes the cost and engineering curves from the aforementioned manual, for the purposes of producing construction cost estimates for small scale hydropower schemes. It is this macro that we utilize to derive our second set of cost estimates, based on many of the same input parameters mentioned previously.

For robustness and comparison purposes, we also estimate construction cost estimates for the observations in our dataset a third way, through interpolation. In 2004 England, through a consortium of private and publicly funded agencies, produced a manual on the small hydropower potential in Southeast England (Bacon and Davison, 2004). This manual contains a number of graphical presentations of engineering and costing relationships.[22] Scotland produced a similar report in 2008 (Forrest et al., 2008), also with graphical representations of engineering and cost relationships. And finally, the US Army Corps of Engineers produced a technical manual on the development of small hydropower generation in the 1970s, when the first oil crisis hit and before the collapse of oil prices in the 1980s dampened national interest in small hydropower development (USACOE, 1979).[23] We gather together all of these reports and use them to interpolate cost estimation equations for the observations in our dataset, given the familiar parameters mentioned previously. Our total cost function (y) is a composite of construction costs (c), penstock costs (h), switchyard equipment costs (a), and

[16] We also considered extending the database to include soil conditions, as soil type can be an input parameter into the costing models as well, but we found that ultimate results were never very sensitive to this parameter so we did not gather it at a site-specific level.

[17] In 2004, for example, the federal government approved $343 million for renewable energy research, but of that, only $5 million (1%) went to hydropower. In 2005, even this small amount was completely eliminated (effective FY2007). Recent stimulus measures are directing some money back to hydropower research and development (around $40 million for 2009), but relative to other renewable energy resources, it is still astonishingly small.

[18] This lack of funding, leading to a subsequent inability to develop hydro costing estimates, was confirmed in a 2008 telephone conversation with DOE engineers.

[19] Examples include Canada, Norway, New Zealand, and Brazil, all places where in fact a majority of the electricity produced is derived from hydropower. In some of these countries, "hydro" has even become the colloquial term for "electricity," indicating the perceived interchangeability of the two.

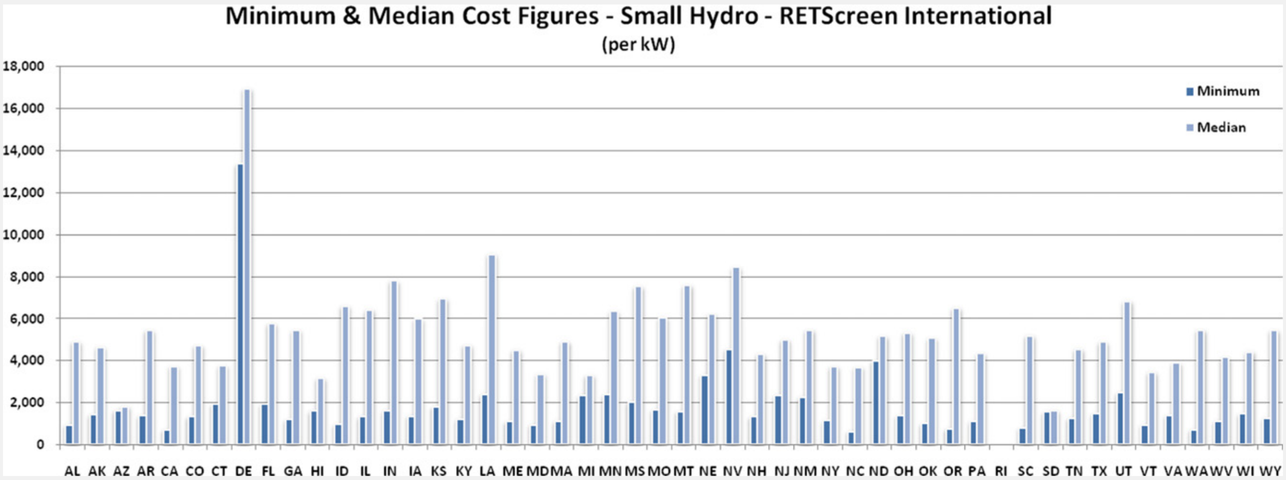
[20] For details on the algorithms that make up this software program, see MNRC (2004).

[21] Ultimately these parameters turned out to have very little effect on the cost estimates, so the upper and lower bounds are not reported distinctly in this paper. The final RI cost estimates given are instead an average of the two.

[22] Examples include the amount of power available given the head and flow conditions of a site, the cost of required turbine equipment given capacity installed, and installation cost estimates given head and power capacity available.

[23] This publication is obviously rather old, but since hydroelectric power generation is such a mature technology, the engineering relationships are unlikely to have changed much since the manual was first written.

Table 3



transmission line costs (t) and is of the form

$$y=(\alpha_0 x^{\alpha_1} z^{\alpha_2})+((\beta_0 \rho x^{\beta_1} z)/1000)+(\gamma_0+\gamma_1 b+\gamma_2 z)+(\delta_0+\delta_1 m+\delta_2 z)+\varepsilon \quad (2)$$

where,

$$c=\alpha_0 x^{\alpha_1} z^{\alpha_2} \varepsilon$$

$$h=ipz$$

$$a=\gamma_0+\gamma_1 b+\gamma_2 z+\varepsilon$$

$$t=\delta_0+\delta_1 m+\delta_2 z+\varepsilon$$

and, x=head, z=power, p=penstock length, b=voltage, m=transmission line length.

These results, too, are discussed below.

5. Results

The RI program, originally developed in 1996, added its small hydro costing model in 2004. The costing equations utilized in the program are based on over twenty years of (generally proprietary) empirical data gathered from previously built small and large hydropower facilities. The results given for our small scale hydropower potential dataset come out on the high side. This can largely be attributed to two factors unique to the RI estimates: the program includes "feasibility study" costs, and not just outright construction costs, and, the program is designed to estimate "life-cycle" costs instead of simple initial construction costs. If the feasibility study estimates were taken out of the results, project costs would decline by about 3–4% on average.[24] It is difficult to determine how much further the estimates would fall if initial construction costs alone, and not life-cycle costs, were estimated, but it is certain that the final numbers would be smaller still. For these reasons, the estimates from the RI program constitute our upper bound.

Table 2 presents some summary information on the cost estimates for the three categories of project, "small," "mini," and "micro." [25] In the extreme, the cheapest small scale hydropower site comes in at $638 per kW to construct, while the most expensive small scale hydropower site comes in at a whopping $6,103,161 per kW. Of more interest are the medians for the different categories of hydropower project; here we can see the economies of scale in small scale hydropower development. The "micro" projects are extremely cost-ineffective, with over half of the projects costing nearly $50,000 per kW to construct. The "mini" projects do better at around $11,500 per kW to develop, but it is the "small" projects that show the greatest potential with half the projects costing less than $5,000 per kW to develop. This is still high relative to many fossil fuel based plant construction costs, and even relative to some renewables, but a breakdown of the data (Table 3) illustrates that there are hundreds of sites, in states across the country, that break the $2,000 per kW cost-effectiveness barrier. And the numbers improve when we look at the results from the Norwegian macro.

Table 4
Norwegian macro—summary results (per kW).

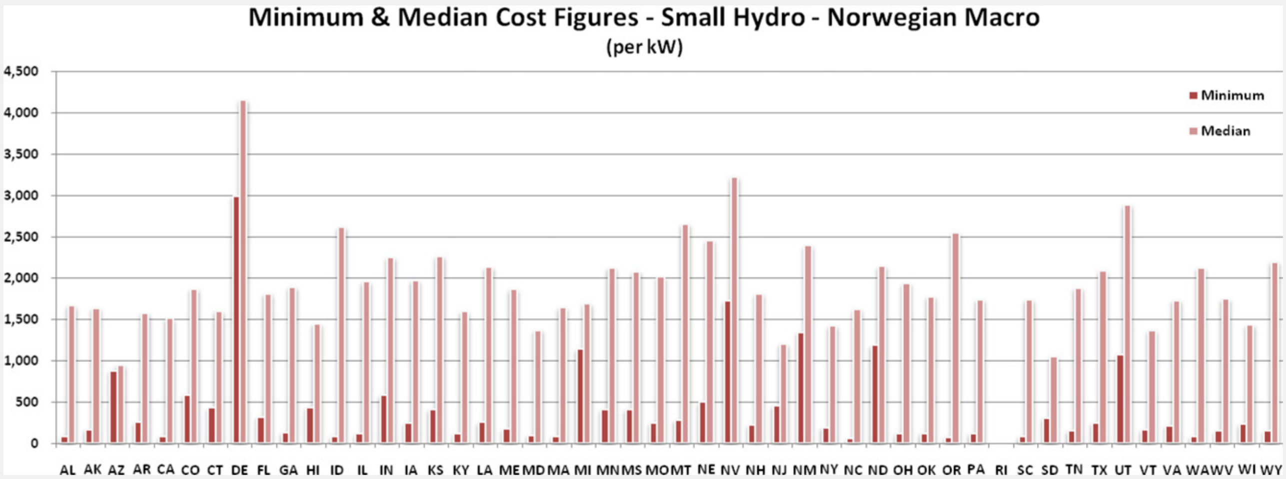
"Small" hydro 30 MW ≥ P ≥ 1 MW	"Mini" hydro 1 MW > P > 100 kW	"Micro" hydro 100 kW ≥ P
n=5427 Min=$57 Max=$169,487 Mean=$2618 Median=$1896	n=28,616 Min=$755 Max=$423,843 Mean=$6912 Median=$5615	n=1691 Min=$3114 Max=$308,668 Mean=$59,318 Median=$37,576

The Norwegian Macro (NM), first created in 1980 and regularly updated at five year intervals, was specifically written to address the need for uniform economic evaluation of small scale hydropower projects. Its use is not as widespread as RI – which to date reports more than 40,000 users in over 100 countries – but it has been applied to projects in Europe, Latin America, Africa, and East Asia. It too is based on (proprietary) empirical data gathered from numerous small scale hydropower sites constructed in the past. The results given for our small scale hydropower potential dataset come out on the low side, and so they constitute our lower bound. Table 4 presents the summary

[24] For small scale hydro development, the RETScreen International manual itself notes that this additional cost may be taken out (MNRC, 2004).

[25] A note should be made regarding dropped observations. Of the "small" data points, only 16 out of an initial 5,443 observations had to be dropped due to missing data (less than ½%). Of the "mini" observations, 21 out of an initial 28,637 were dropped. The microhydro observations, however, suffered from a large amount of missing data; 91,941 out of 93,632 observations were incomplete.

Table 5



statistics for the three classifications of power project and while the overall numbers are lower than the RI results, the trends are the same. "Small" hydropower is more cost-effective, on average, than either "mini" or "micro" hydro, and within the "small" category there appears to be numerous sites that are cost competitive right now. Table 5 displays the small scale hydropower results broken down by state.

The interpolation program results, which are not separately reported but are available from the author, tend to come out between the RI and NM estimates, though on average closer to the lower NM estimates. These results confirm the same trends already related above, but at the same time understate the fact that our numbers are only estimates and, especially with regard to any one particular site, likely contain a degree of error.

All of the costing programs were sensitive to the base parameters listed in Table 1 to similar degrees. Head and flow were by far the most influential parameters on total cost estimates, while nearest road, penstock length, nearest powerline, nearest substation, nearest plant, nearest railroad, nearest population, and number of frost days at site all had relatively smaller impacts. Graphs of the general relationships of the base parameters to total costs are shown in Fig. 2.

In summary, our two main conclusions from this research are that small scale hydropower is subject to nonlinear economies of scale, and that while average costs of development of small scale hydropower appear on the high side, there are still many small scale hydropower sites that are cost-effective to develop in today's marketplace. Tables 6 and 7 display the particular cost-effective sites identified from the RI and NM programs, respectively, by state. $2,000 per kW is chosen as the conservative cost-effectiveness threshold.[26] As can be seen from these tables, there are hundreds of sites available, in most states in the country, where cost-effective, environmentally friendly, zero carbon emissions producing hydropower could be developed.[27]

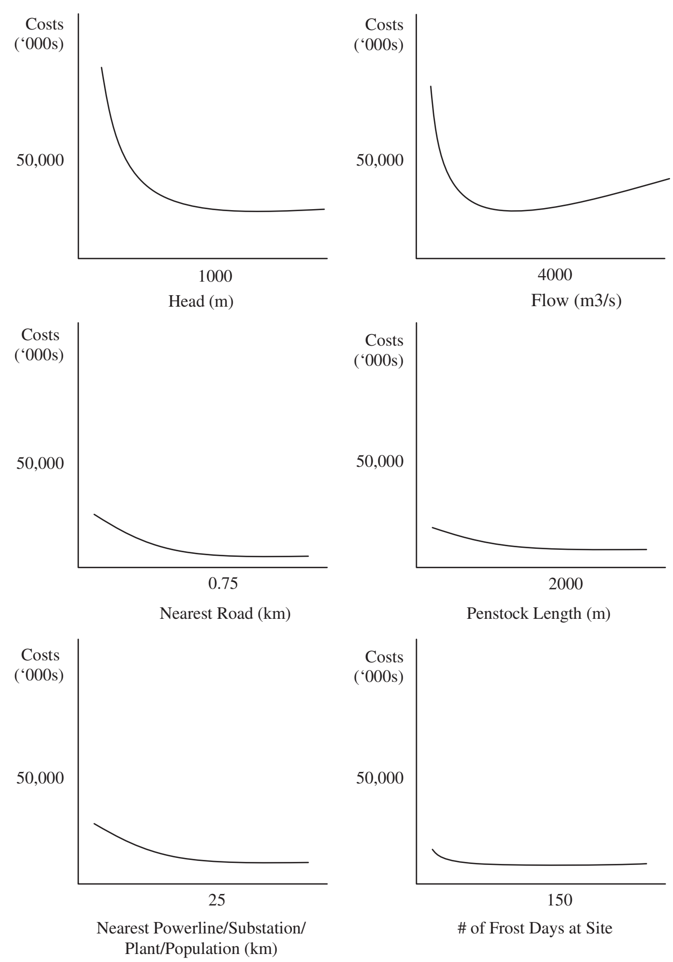


Fig. 2

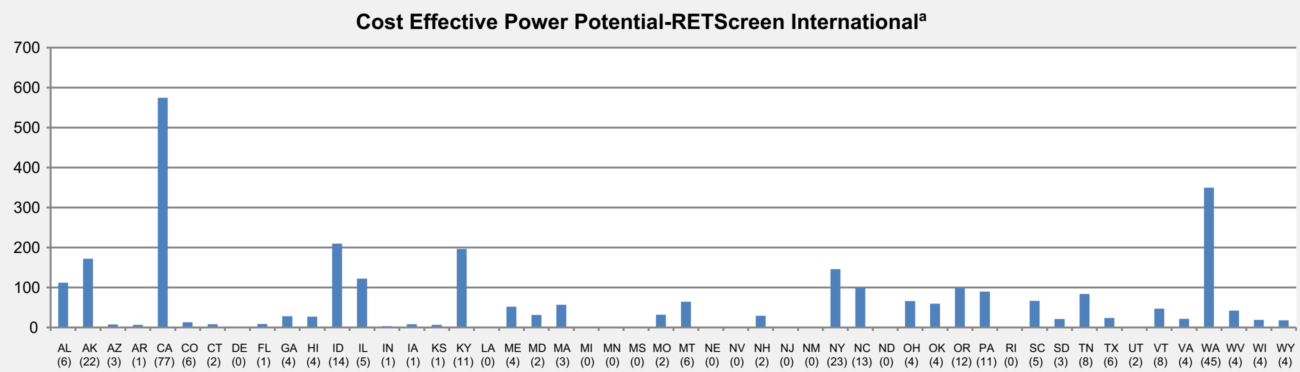
6. Conclusions

This paper has analyzed the current small scale hydropower potential in the United States for its construction (though not life-cycle) cost-effectiveness. Two main conclusions were drawn: (1) small scale hydropower is subject to nonlinear economies of scale so that tiny ("mini" or "micro") hydropower projects should probably remain undeveloped, given current technologies, and (2)

[26] It is worth reiterating that this $2,000 per kW threshold, common in the literature, is biased against hydropower as it does not take into account the low life-cycle operation and maintenance costs of hydropower relative to traditional fossil fuel based plants (EURECA, 2002), nor does it value the numerous positive externalities to hydropower generation such as reduced air emissions and reduced fossil fuel imports.

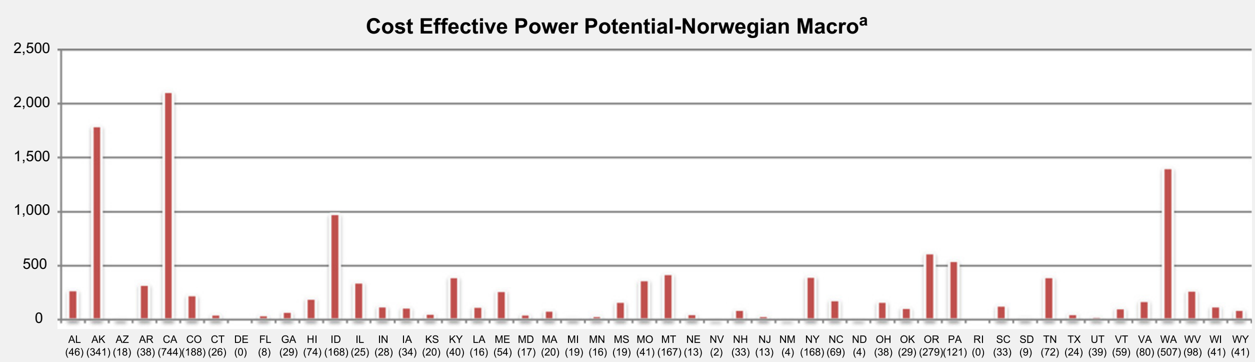
[27] A recent survey of US households (Greenberg, 2009) finds that 70% of respondents wanted the US to increase its reliance on hydroelectric sources of power.

Table 6



[a] Total MW is on the vertical axis, while the number of sites per state is listed below the abbreviation.

Table 7



[a] Total MW is on the vertical axis, while the number of sites per state is listed below the abbreviation.

while the average construction costs of small scale hydropower are relatively high, there remain hundreds of sites on the low end of the cost side (generating upwards of 13,000 MW of power) that are cost-effective to construct right now. Additionally, more sites will become cost-effective in the future as the ancillary benefits of hydropower (such as lack of carbon and other air emissions, diurnal reliability, and non-foreign fuel importation requirements) gain in market value.[28]

The overall value of both of the above results depends in part on estimates of the speed of global climate change. Debate continues over the speed of global warming and thus the timing available for action to address it (Stern, 2009; Nordhaus, 2007). Determining exactly how fast we should be pursuing a global reduction in greenhouse gas emissions is beyond the scope of this paper, however, if we are risk averse about judging the speed of climate change and decide that immediate action is necessary to reduce harmful carbon emissions, then developing our small scale hydropower potential can buy time. If a more immediate solution to the climate change crisis is demanded, adding to the country's small scale hydropower capacity (as opposed to waiting and spending scarce resources instead on longer-shot technologies) is one way to proceed. Environmentally friendly sites have now been identified, the technology, materials, and companies to develop these sites exist, and work to put them in place could begin.

[28] Ongoing research (Kosnik, 2010b) seeks to more accurately value the positive externalities from these important ancillary benefits.

If policy is decided to develop the environmentally friendly, cost-effective, small scale hydropower sites identified in this paper, a few recommendations can be made for practically proceeding forward on this front. The first is that a simultaneous effort should be made to streamline the permitting process for small scale hydropower plants. Currently, permitting for small scale hydropower projects is subject to the tragedy of the anticommons (Kosnik, 2010a, in press; Parisi et al., 2006; Heller, 1998), where too many regulatory agencies at federal, state, and local levels are repetitively involved in the regulating process. This results in fragmented, costly, and most detrimentally, inefficiently time consuming regulatory procedures. This bureaucratic sclerosis is in part a result of the mimicking of the permitting process for small scale hydropower on large scale hydropower. However, the two are entirely different beasts with different local impacts, different environmental effects, and different stakeholders. Small scale hydropower needs to be divorced from its current regulatory coupling with large scale hydropower and given its own permitting schedule. Streamlining this regulatory process would go a long way towards improving the incentives for small scale hydropower development.

Second, on the private sector side, small scale hydropower would benefit from a greater standardization of parts. Again due to a holdover from small scale hydropower emerging as a technological derivative of large scale hydropower, most companies today approach the construction of small scale hydropower sites as if they were large scale hydropower sites, requiring individual attention to the minutest level. There are gains to be had to the company that develops a streamlined, standardized, catalog of parts for small scale hydropower development. Whether this needs to occur first in order to drive demand, or increased demand for small scale hydropower development will subsequently lead to the standardization of parts is an open question, but regardless, a streamlined construction experience would also aid in encouraging the development of the country's small scale hydropower potential.

In conclusion, as we proceed in the effort to reduce global warming, it remains worthwhile to explore all of our available options in an effort to diversify avenues of approach to this difficult and pressing problem (Barrett, 2009; Tonn et al., 2009). The main benefit of small scale hydropower, as one component in a portfolio of diverse renewable energy supplies, is that the technology to develop it is mature and it can be implemented relatively quickly, allowing us to address climate change concerns. This paper provides critical information in moving forward the assessment of *small* hydropower's potential to reduce climate change—an area not always appreciated because of a bias of perception towards equating all hydropower development with ecologically harmful *large* hydropower development. Small hydropower will never be the complete answer to emissions-free energy production in the United States, but a case can be made that it can be a useful part of the answer.

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