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A comprehensive view of global potential for hydro-generated electricity

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In this study, we assess global hydropower potential using runoff and stream flow data, along with turbine technology performance, cost assumptions, and consideration of protected areas. The results provide the first comprehensive quantification of global hydropower potential including gross, technical, economic, and exploitable estimates. Total global potential of gross, technical, economic, and exploitable hydropower are estimated to be approximately 128, 26, 21, and 16 petawatt hours per year, respectively. The economic and exploitable potential of hydropower are calculated at less than 9 cents per kW h. We find that hydropower has the potential to supply a significant portion of world energy needs, although this potential varies substantially by region. Globally, exploitable hydropower potential is comparable to total electricity demand in 2005. Hydropower plays different roles in each country owing to regional variation in potential relative to electricity demand. In some countries such as the Congo, there is sufficient hydropower potential (>10 times) to meet all electricity demands, while in other countries such as United Kingdom, hydropower potential can only accommodate a small portion (<3%) of total demand. A sensitivity analysis indicates that hydropower estimates are sensitive to a number of parameters: design flow (varying by −10% to +0% at less than 9 cents per kW h), cost assumptions (by −35% to +12%), turbine efficiency (by −40% to +20%), stream flow (by −35% to +35%), fixed charge rate (by −15% to 10%), and protected land (by −15% to 20%). This sensitivity analysis emphasizes the reliable role of hydropower for future energy systems, when compared to other renewable energy resources with larger uncertainty in their future potentials.

Broader context

Hydropower is currently the dominant renewable energy source and can help facilitate the deployment of other variable renewable energy resources. Improved information on hydropower potential and its spatial distribution can help decision-makers guide the deployment of hydropower plants. Information on hydropower potential is also an important input to integrated assessment and energy–economic models, which are used to help explore future energy systems, climate impacts, and transition pathways to lower-carbon futures over decadal to century time-scales.

1. Introduction

Renewable energy sources such as hydropower, wind, solar, and biomass are important technology options for reducing greenhouse gas emissions and local air pollutants associated with the burning of fossil fuels. They provide stable sources of electricity supply, and are expected to play an important role in future energy systems and environmental sustainability.[1–3] Hydropower is currently the dominant renewable energy source accounting for 18% of the world's total electricity supply.[4] Hydropower is also technically mature and economically competitive. Moreover, hydropower plants can help balance electricity supply and demand, and therefore improve the efficiency of thermal power plants and reduce the impacts of variability in other renewable energy resources such as wind.

Hydropower potential and present day deployment show large spatial heterogeneity with undeveloped capacity ranging from ∼50% in Europe to 90% in Africa.[4] Improved information on hydropower potential can help decision-makers gain insight into the available resource and its spatial distribution, which can help guide the deployment of hydropower plants. Information on hydropower potential can also be used to help explore future energy systems challenged by both climate change and

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emissions mitigation on decadal to century time-scales using integrated assessment and energy–economic models.[5–7]

The spatial distribution of hydropower potential has been evaluated at regional scales in previous studies.[8–17] For example, Lehner, *et al.*[16] calculated gross hydropower in Europe using a model-based approach with consideration of climate and socio-economic changes. Cyr, *et al.*[12] developed a method to map the small hydropower resource using a synthetic hydro network. The gross, technical, and economic hydropower potentials in China were estimated as 6.1, 2.5, and 1.8 petawatt hours (pW h) per year, respectively.[13,14] The hydropower potential in the United States was estimated as 2.7 pW h per year.[15]

As hydropower potentials have been evaluated mostly at the national or regional levels in previous studies,[9–17] significant discrepancies and inconsistencies between the data and methods in these studies cannot be avoided. A number of factors, such as technical innovation, environmental and social considerations, can influence the evaluation of hydropower potential and its deployment opportunities.

Therefore, it is challenging to evaluate global hydropower potential or differences between countries from these studies. There are a number of previous studies examining global hydropower potential,[18–20] often with limited consideration of spatial details. More important, most of these studies investigated the gross potential of hydropower without also estimating the technical potential of hydropower. An important gap in the literature is an estimate of the actual global hydropower potential that could be developed taking into account economic and environmental considerations. The global gross hydropower potential from Pokhrel, *et al.*,[21] around 50 pW h per year, falls in the range between 40 pW h per year by WEC[22] and 80 pW h per year by Labriet, *et al.*[23] With technical consideration, WEC[22] and Bartle[24] estimated global hydropower potential to be 16 pW h per year and 14 pW h per year, respectively. Moriarty and Honnery[25] summarized global renewable energy potential with an estimation of global technical hydropower potential ranging from 4 pW h per year to 26 pW h per year. Theoretical, technical, and economic potentials of hydropower were 40, 15, and 8 pW h per year, respectively, according to Klimenko, *et al.*[26] Estimated global potential of hydropower varies greatly due to different definitions and methods used in these studies. A consistent and comprehensive understanding of global hydropower and its spatial distribution are the key to understanding the important factors in hydropower development and regional differences.

This study has two purposes. The first purpose is to develop a comprehensive and consistent estimate of global hydropower potential including: gross, technical, economic, and exploitable, that is potentially useful for a number of applications, including energy modeling. The second purpose of this study is to improve our understanding of the major factors and sources of uncertainty that influence estimates of hydropower potential across space.

The remainder of this paper summarizes the approach and findings from this study. In Section 2, we describe the methodology, including an overview of the hydropower calculation, major data inputs of runoff and stream flow, the methods to calculate gross, technical, economic, and exploitable hydropower potential. In Section 3, we discuss the results and findings from this study, including four types of hydropower potential, impacting factors, and sensitivity to different parameters. In Section 4, we conclude the paper with final remarks.

2. Methodology and data

2.1. Methodology overview

In this study we develop a grid-based method to calculate four types of hydropower potential (gross, technical, economic, and exploitable) (Fig. 1). The framework relies on runoff and stream flow information from a global hydrologic model[27] that includes river routing. The gross potential of hydropower is calculated from runoff with elevation data. The technical potential is estimated from monthly stream flow together with head (elevation difference between the neighboring grid in the flow direction) and consideration of design capacity. The technical potential is then adjusted to economic potential based on generation cost which is estimated according to the design capacity and cost and financing assumptions. Finally, the exploitable potential is derived from economic potential with and adjustment due to environmental restrictions of projected and urban areas. Each step will be detailed in the following sections.

2.2. Runoff and stream flow

In this study, we use a global hydrologic model – namely, the global water availability model (GWAM) – to simulate runoff over all land grids with the exception of Antarctica and Greenland. GWAM is a gridded monthly water balance model with a 0.5 × 0.5 degree spatial resolution. It requires gridded monthly precipitation, temperature, and maximum soil storage capacity and computes evapotranspiration to the atmosphere, runoff, and soil moisture in the soil column at the monthly scale. GWAM runs over the entire 20th century using the Climatic Research Unit dataset (CRU TS 2.0)[28,29] to generate the monthly runoff for each individual grid (Fig. 2). More details about the GWAM model can be found in Hejazi, *et al.*[27]

To permit a realistic representation of water supplies that are available for hydropower generation, GWAM has been updated by including a spatial river routing component – a modified representation of the river transport model (RTM) that employs a cell-to-cell routing scheme with a linear advection formula. Motivated by the work of Li, *et al.*[30] and

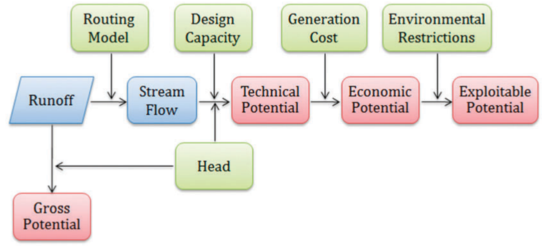

Fig. 1 The methodology to develop four types of hydropower potential.

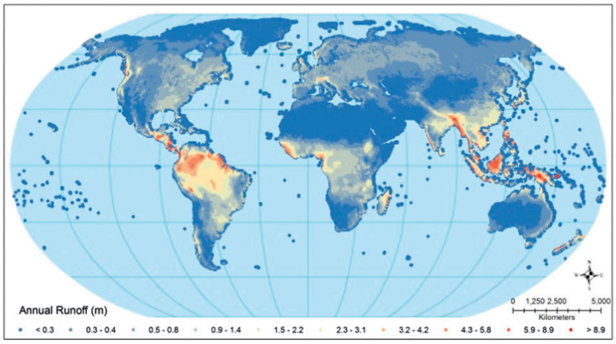

Fig. 2 Thirty-year (1971–2000) mean runoff.

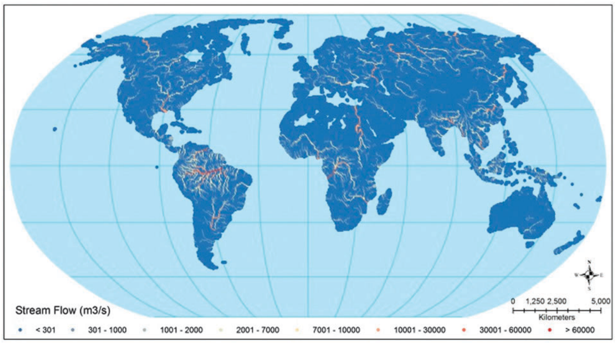

Fig. 3 Thirty-year (1971–2000) mean annual stream flow.

Swenson *et al.*,[31] we modified RTM in two important aspects by: (1) replacing the global uniform channel velocity field with a spatially distributed channel velocity field generated by Li, *et al.*[32] based on a physically based routing model; (2) adapting a more realistic river network delineated with a hierarchical dominant river tracing algorithm. For more details about the modified RTM, please refer to Appendix. Fig. 3 shows a global gridded spatial map of the mean annual stream flow over the simulated historical record.[33]

2.3. Gross potential

Gross theoretical hydropower potential is defined as the annual energy that is potentially available if all natural runoff at all locations can be harnessed down to sea level (or to the border of a region when calculating regional potential) without any energy losses.[34] In this study, the gross hydropower potential is calculated in each grid globally using eqn (1).[21]

$$E_{g_i} = m_i \times g \times \Delta H_i \tag{1}$$

where E_{g_i} is gross hydropower potential (watt hour) in grid i, m_i is the mass of monthly runoff water in grid i (kg), g is average gravitational acceleration (m s^{-2}), and ΔH_i is the elevation difference between grid cell i and lowest grid cell in each country (m). The elevation data we used here are derived from hydrological data and maps based on shuttle elevation derivatives at multiple scales (HydroSHEDS).[33] It is worth noting that the gross potential of hydropower in each grid is theoretical, not the hydropower that could actually be generated in that grid.

2.4. Technical potential

Technical potential of hydropower is defined as the annual energy that could be developed under current technology, regardless of economic and other restrictions.[35] In this study, the technical potential of hydropower is calculated from monthly stream flow and head based on the physical assumption that hydropower potential at each grid cell is determined by the potential energy of stream flow relative to the neighbouring grid in the flow direction. Because stream-flow is not uniform either within or across years, hydropower facilities are designed to capture much, but not all potential power. Our estimate of technical potential incorporates practical design considerations, and is therefore not the absolute limit on what could be technically deployed. We follow other studies[36,37] in this regard and employ the assumption of 30% monthly stream flow exceedance, *i.e.* there is a 30% chance that monthly stream flow will exceed the turbine design capacity and will not be utilized for power production. Sensitivity analysis, shown below, indicates that this assumption has only a small impact on low-cost hydro potential. Hydropower potential considering cost will be analyzed in the next section as economic potential. The design capacity of hydropower is calculated using eqn (2).[36,37] The technical potential of hydropower in each grid is then adjusted according to the hydropower design capacity at that grid (eqn (3)).

$$P_{\text{design}} = \eta \times Q_{i30} \times \Delta h_i \times \gamma \tag{2}$$

$$\begin{cases} E_{t_i} = P_{\text{design}} \times T & \text{if} \quad \eta \times Q_i \times \Delta h_i \times \gamma > P_{\text{design}} \\ E_{t_i} = \eta \times Q_i \times \Delta h_i \times \gamma \times T & \text{if} \quad \eta \times Q_i \times \Delta h_i \times \gamma \leq P_{\text{design}} \end{cases} \tag{3}$$

where P_{design} is the hydropower design capacity (watt), E_{t_i} is the monthly technical hydropower potential (watt hour) in grid i, and η is the net generation efficiency (unitless), which is assumed to be a constant 0.80.[12] γ is the specific weight of water (9800 N m^{-3}), and Δh_i is the head (m), which is calculated as the elevation difference between grid i and the neighboring downstream grid. Q_i is the monthly stream flow (m^3 s^{-1}), T is hours in a month (hour), and Q_{i30} is the 30% monthly stream flow exceedance quantile. Finally, the monthly technical hydropower potential is aggregated to the annual total in each grid.

2.5. Economic potential

Although a certain amount of hydropower potential is available at most river locations under current technical conditions, ultimately, hydropower must compete on an economic basis with other sources of energy. Economic potential of hydropower is defined as the annual energy that can be developed at costs competitive with other energy sources[16,34] and requires an estimate of the cost to generate electricity from hydropower in each grid. In this study, the cost to generate hydropower is calculated taking into account costs for licensing, construction, environmental harm mitigation, fixed and variable operation and maintenance, turbine, and generator. The empirical cost equations used by U.S. Bureau of Reclamation,[37] which were developed originally by Hall, *et al.* for currently undeveloped sites in the United States,[38] are utilized as the baseline cost estimates. The economic potential of hydropower can be then derived for different cut-off costs. The cost of energy (Coe) in \$ per kW h is calculated as below,

$$\begin{cases} C_{\text{development}} = \phi \times A \times P_{\text{design}}^{B} \times \Delta h_i^{C} \times S^{D} \\ C_{\text{O\&M}} = A \times P_{\text{design}}^{B} \times \Delta h_i^{C} \times S^{D} \\ \text{Coe} = \dfrac{C_{\text{development}} + C_{\text{O\&M}}}{E_{\text{t}}} \end{cases} \tag{4}$$

where $C_{\text{development}}$ and $C_{\text{O\&M}}$ are the cost (2002 US\$) for the hydropower development and annual operation and maintenance, ϕ is the fixed charge rate (FCR) (unitless), E_{t} is the technical hydropower potential (watt hour), P_{design} is the design capacity, and it is calculated based on the 30% monthly stream flow exceedance quantile (Q_{30}), as discussed in Section 2.4. Δh_i is the head (m), S is the generator rotational speed (rpm), and A, B, C and D are the empirical parameters (Table 1), from the studies by U.S. Bureau of Reclamation and Hall, *et al.*[37,38] Theses parameters were derived by fitting the costs (Table 1) as a function of plant capacity based on a dataset from a number sources such as Federal Energy Regulatory Commission (FERC) and Energy Information Administration.[38] ϕ accounts for the time value of money and real-world financing constraints that affect the costs of energy technology development projects. In this study, we assume a same fixed charge rate of 0.13 as in the study by Zhou *et al.*,[1] which corresponds to a simple interest rate of 12.5% amortized over 30 years. This assumption is considered pessimistic given the long life and low interest rate for hydropower development, which is generally undertaken by governments. The sensitivity of the hydropower potential to this parameter will be examined in the sensitivity analysis.

The parameters in the equations for cost estimation vary by turbine types. A specific turbine type can be determined in each grid according to the design flow (Q_{30}) as well as head (Δh_i). We use a 2-dimension selection matrix (x: stream flow; y: head) developed by U.S. Bureau of Reclamation[37] to select the turbine type in each grid. The turbine type can be determined based on the magnitude of stream flow on the x-axis and size of head on the y-axis. In this study we assume four types of common turbine types: Francis, Kaplan, Pelton, and low head for future hydropower development.[37,38]

Table 1 Cost calculation parameters

Cost	A	B	C	D
Licensing	$6.1 \times 10^{+5}$	0.70	0	0
Construction	$3.3 \times 10^{+6}$	0.90	0	0
Fish & wildlife mitigation	$3.1 \times 10^{+5}$	0.96	0	0
Recreation mitigation	$2.4 \times 10^{+5}$	0.97	0	0
Historical & archeological mitigation	$1.0 \times 10^{+5}$	0.72	0	0
Water quality monitoring	$4.0 \times 10^{+5}$	0.44	0	0
Fish passage mitigation	$1.3 \times 10^{+6}$	0.56	0	0
Turbine upgrade				
Francis turbine	$3.0 \times 10^{+6}$	0.71	−0.42	0
Kaplan turbine	$4.0 \times 10^{+6}$	0.72	−0.38	0
Pelton turbine	$2.4 \times 10^{+6}$	0.71	−0.42	0
Low head turbine	$6.0 \times 10^{+6}$	0.86	−0.63	0
Generator upgrade	$3.0 \times 10^{+6}$	0.65	0	−0.38
Fixed operation and maintenance	$2.4 \times 10^{+4}$	0.75	0	0
Variable operation and maintenance	$2.4 \times 10^{+4}$	0.80	0	0

2.6. Exploitable potential

Not all areas can realistically be used for hydropower development. Exploitable hydropower potential is defined as the competitive annual energy with the consideration of environmental or other special restrictions.[16] In this study, we use a dataset of protected area from the world database of protected area (WDPA) by UNEP and IUCN as the major environmental restriction as it is the only comprehensive collection of global locations which receive protection because of their environmental or cultural values. Protected areas such as national parks, wildlife management areas, and aesthetic forests are included in this dataset. We calculated the percentage of protected land in each grid, and exclude the grids with protected land larger than 20% for hydropower development. The sensitivity of exploitable hydropower potential to this parameter will be discussed in detail in the sensitivity analysis. Hydropower plants are also not suitable in areas with high population density. Therefore, we excluded highly urbanized area as another environmental restriction for hydropower development. The data of urban area are from a global product of urban extent using nightlights data.[39,40] With the exclusion of protected and urban areas, we remove about 18% of land area from total area in consideration of hydropower development. In this way, the economic hydropower potential is adjusted as exploitable potential with these areas excluded.

It is worth noting that hydropower development can also be constrained by other ecological, socio-economic, and legal/geopolitical concerns that may arise with regard to potential hydropower development, in addition to those considered in the data of protected area and urban extent. These will be discussed in more detail below.

3. Results and discussion

The methods described above were employed to create a comprehensive, hierarchical estimate of global hydropower potential including gross, technical, economic, and exploitable at a 0.5 × 0.5 degree spatial resolution. With hydropower potential estimated at the grid level, national or regional statistics can be derived and evaluated. In this section, we first present the results of four types of hydropower potential estimation. Second, we analyze the cost supply curves of hydropower potential. Third, we perform the sensitivity of hydropower potential to six relevant parameters. Finally, we compare our estimation of hydropower potential to other globally available studies and electricity demand.

Fig. 4 presents an overview of global hydropower potential by type and cut-off cost. Total global gross hydropower

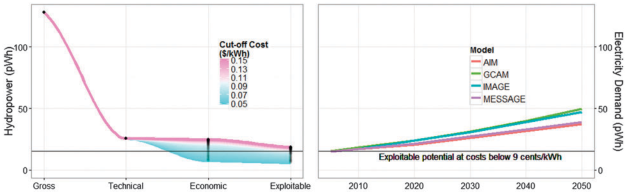

Fig. 4 The global hydropower potential at different cut-off costs (left) and projected electricity demand from 2005 to 2050 (right).

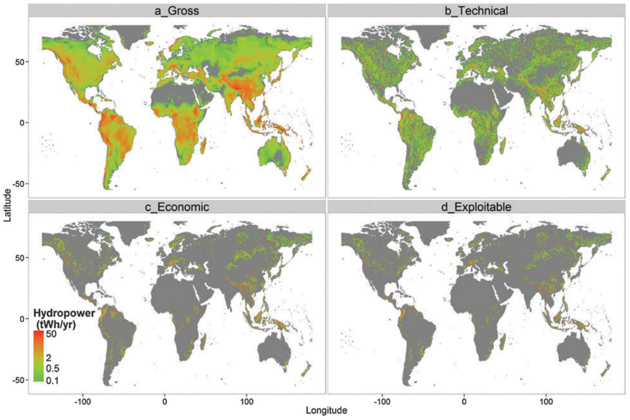

Fig. 5 Long term (1971–2000) mean annul hydropower potential at the grid level.

potential is estimated to be approximately 128 pW h per year. The technical potential is 26 pW h per year. The economic potential ranges from 8 to 25 pW h per year with a cut-off cost from 0.05 to 0.15$ per kW h per year. The corresponding exploitable potential ranges from 6 to 18 pW h per year.

Global exploitable hydropower at costs below 9 cents per kW h is 16 pW h per year (1.8 TW), which is comparable to world total electricity demand (15.7 pW h) in 2005[41] and about 1/3 to 1/2 of projected 2050 electricity demand depending on the model.[42]

3.1. Global hydropower potential

Globally, long-term mean gross hydropower potential from 1971–2000 is about 128 pW h per year. The gross hydropower potential shows large variability across space (Fig. 5a). Generally, countries with either large elevation or high runoff possess large gross hydropower potential. Gross hydropower potential is driven largely with elevation except for South America where high runoff is the dominant factor. The largest gross hydropower potential occurs in the region around Tibetan Plateau which is characterized by large elevation. The gross hydropower potential is high in the western mountains of North America, almost all of South America, as well as central Africa, while it is low in Europe. At the country level, as shown in Fig. 6, China with large elevation and Brazil with large runoff have the highest gross hydropower potential. Countries such as Peru, though small, still possess a large gross hydropower potential because of large elevation. The gross hydropower potential is high on the island of New Guinea due to large elevation, which makes Indonesia one of the top-10 countries for gross hydropower potential.

Technical hydropower potential at the grid level is shown in Fig. 5b. Technical hydropower potential is calculated from stream flow, and therefore, the potential is generally large in areas with large rivers, and the spatial distribution is still heterogeneous. The total long-term mean technical hydropower potential from 1971–2000 is 26 pW h per year, about one-fifth of gross potential. The design capacity is an important impacting factor of hydropower technical potential. We find that grid cells with large design capacity are generally located in areas with large head and large rivers (Fig. 7) such as the Snake River

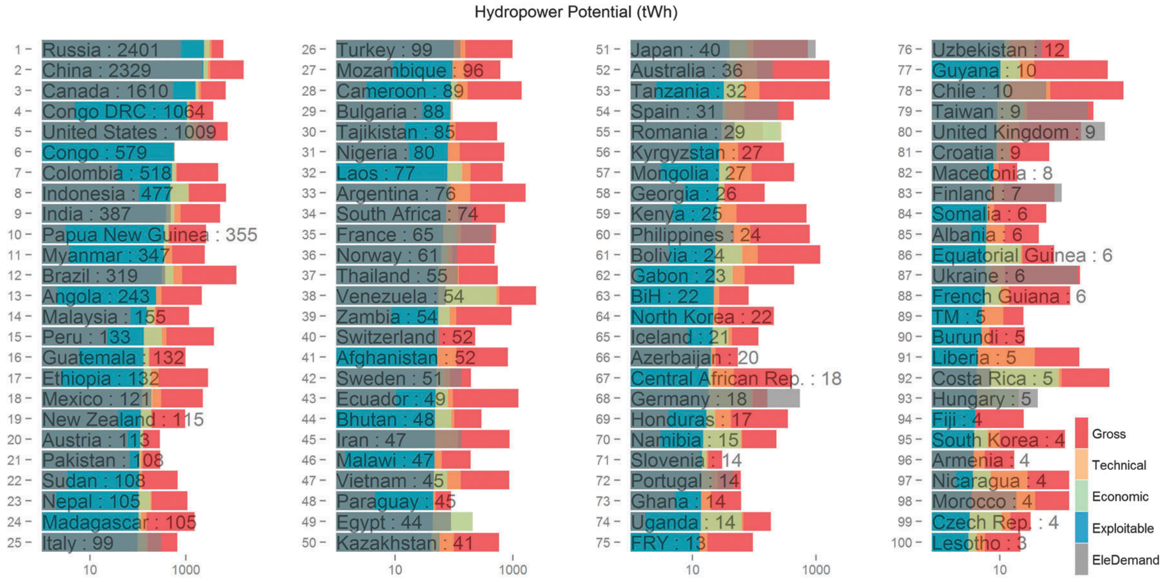

Fig. 6 The top-100 hydropower potential countries (hydropower and electricity demand are in log scale and the number on the bar is exploitable hydropower potential).

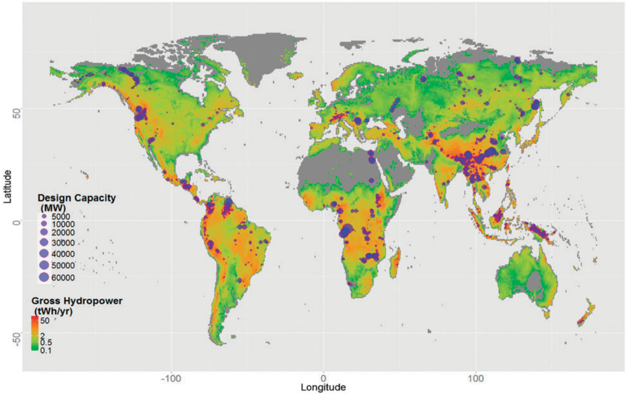

Fig. 7 Grid cells with design capacity larger than 1000 MW overlaid on the map of gross hydropower potential.

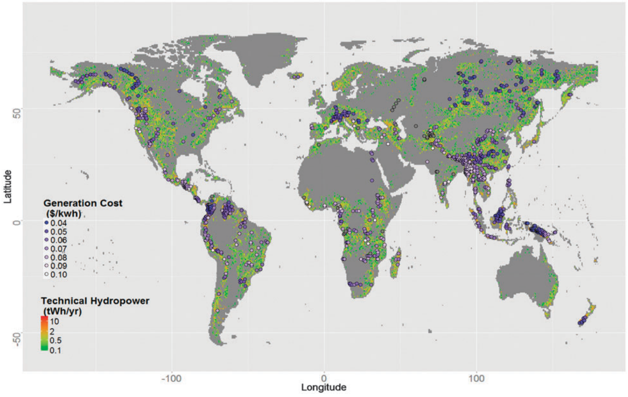

Fig. 8 Generation cost of gird cells with installed capacity larger than 1000 MW overlaid on the map of technical hydropower potential.

in Washington State, USA, and the upper Yangtze in China. Some countries such as Peru are not in the top-10 in terms of technical potential because major rivers in these countries flow into downstream countries.

Economic hydropower potential at the grid level is shown in Fig. 5c. A particular focus of this study is the long-term potential of hydropower, and we focus in this discussion on the economic hydropower potential at cost lower than 9 cents per kW h. The total long-term mean economic hydropower potential from 1971–2000 is 21 pW h per year, about one-sixth of gross potential. Economic potential is always smaller than technical potential (Fig. 5b and c). Not surprisingly, the economic potential of hydropower also shows large regional differences. A number of counties have economic hydropower larger than 1.5 pW h, *i.e.* Russia (3.1 pW h), China (2.9 pW h), and Canada (1.8 pW h), at costs lower than 9 cents per kW h.

The cost of hydropower generation is influenced by both design capacity and head. According to the equation used for generation cost calculation (eqn (4)), total cost increases with design capacity. However, unit cost of electricity generation from hydropower, with total cost normalized by generation, will decrease with design capacity as parameter B in eqn (4) is smaller than 1. Large head reduces not only unit cost for electricity generation, but also total cost in hydropower development with a negative parameter of C in eqn (4). Therefore, hydropower stations with low generation costs are still in regions with large technical potential, but head can also play a more important role in terms of economic potential compared to its role in technical potential (Fig. 8), for example, the areas surrounding Tibetan Plateau with large head.

Exploitable hydropower potential at the grid level is shown in Fig. 5d. The total long-term (1971–2000) mean exploitable hydropower potential is 16 pW h per year, about one-eighth of gross potential. Fig. 9 plots urban and environmentally restricted areas together with economic potential. Consideration of environmental restriction and urban area restrictions has a relatively small overall impact on hydropower potential compared to other factors, but the impact is heterogeneous in space. For example, there are a number of large protected areas in the Amazon region where the economic hydropower potential is also high. Therefore, this particular version of environmental restriction plays an important role in exploitable hydropower potential in this region. The economic hydropower potential in Brazil is reduced by about 40%, from 0.55 pW h to 0.32 pW h. While in some other countries, environmental restriction has negligible impact on exploitable hydropower. For example, the exploitable hydropower potential in Argentina is almost identical to economic potential by taking restriction of protected lands into account.

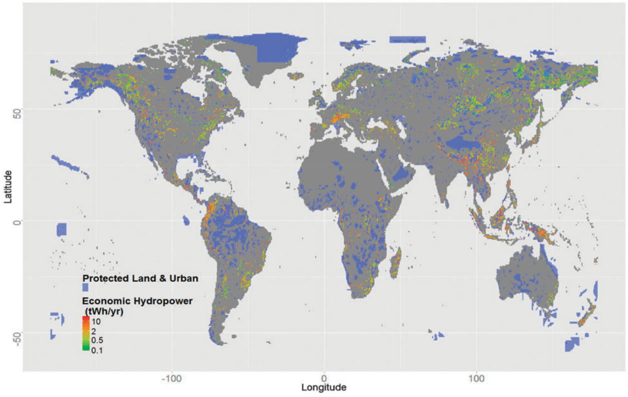

Fig. 9 Protected and urban area overlaid on the economic hydropower potential.

The exploitable hydropower potential plays different roles in each country compared to electricity demand (Fig. 6). For example, the hydropower potential is larger than electricity demand in Canada while the potential in the United States is not enough to meet its electricity demand. In some countries such as the Democratic Republic of the Congo (DRC), the hydropower potential is more than sufficient (>10 times) to meet all electricity demands.

To evaluate the reliability of the global WDPA protected land data as the major environmental restriction, we estimate the exploitable hydropower potential using data from the Protected Areas Database of the United States (PADUS) (http://gapanalysis.usgs.gov/padus/), a comprehensive dataset of protected areas in the United States. The exploitable hydropower potential is close

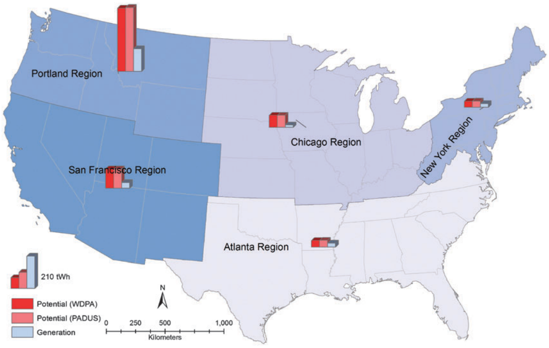

Fig. 10 Hydropower generation and exploitable hydropower potential using the WDPA and PADUS protected land data as environmental restriction at the United States FERC regional level.

using two datasets (Fig. 10), demonstrating the feasibility of using the global WDPA product.

3.2. Hydropower cost-supply curves

The economic potential of hydropower is evaluated in more detail by constructing country-level cost-supply curves, which indicate the amount of the electricity that could be generated at the country level by using hydropower, displayed as a function of a generation cut-off cost. Fig. 11 shows the cost-supply curves of hydropower for the top-10 countries of exploitable hydropower with electricity demand in 2005 overlaid. The change of supplied hydropower electricity with cut-off cost varies greatly by countries. For example, the supplied hydropower with cost lower than 0.06$ per kW h in DRC and Canada is about 0.8 pW h and 1.1 pW h, respectively, when the cut-off cost is doubled (0.12$ per kW h), the hydropower generated electricity in Canada increases by 0.7 pW h and in DRC only increases by 0.3 pW h. For most of these top-10 countries, the increase in hydropower available with an increase in cost is small for cut-off cost above 0.09$ per kW h. All of these countries, except the United States, have adequate hydropower to supply total 2005 domestic electricity demand at this cost. And for the United States, approximately one-quarter of electricity demand (about 3.8 pW h) can be supplied by hydropower at a cost around 0.09$ per kW h (Fig. 11). This is very different from other renewable energy resources. For example, wind power in the United States can potentially supply more than 6 times 2005 electricity demand.[1] A comprehensive analysis of renewable energy and its spatial distribution is necessary to develop better strategies for renewable energy development from local to global scales.

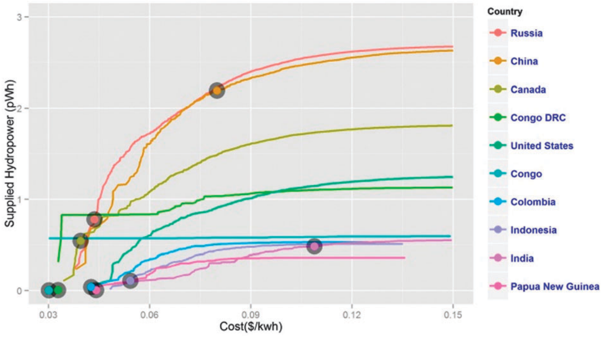

Fig. 11 Hydropower cost-supply curves and 2005 electricity demand (circles) in the top-10 counties. Electricity demand in the United States is about 3.8 pW h, which is not shown in the figure.

3.3. Sensitivity analysis

A sensitivity analysis is performed for six key variables that can have large impacts on our estimates of hydropower potential, as shown in Table 2. We conduct a literature review on each of these parameters to select high and low bounds. A lower exceedance level for design flow, such as Q_{20}, would typically result in a higher installed capacity, and it has been used in the sensitivity analysis in a previous study.[37] In our study, we choose Q_{20} for our optimistic case, and for our pessimistic case choose Q_{40}. The parameters for upper ($\delta_{67\%,\mathrm{UB}}$) and lower ($\delta_{67\%,\mathrm{LB}}$) bounds and encompass 67% of the data points in estimating cost parameters were provided in a previous study.[38] Here, we multiply the parameter A in cost calculation by $(1 + \delta_{67\%,\mathrm{UB}})$ for the pessimistic case and $(1 - \delta_{67\%,\mathrm{LB}})$ for the optimistic case. The plant efficiency in previous studies ranged from low at 0.5 to high at 0.95.[12,43–45] For efficiency sensitivity, we choose 0.5 and 0.95 in our pessimistic and optimistic cases, respectively. We compare stream flow from our GWAM with observed data from the Global Runoff Data Center (GRDC), and found that most of the modelled stream flow data fall in the range of ±30% of observations. Therefore, we vary the stream flow in the central case by ±30% for our optimistic and pessimistic cases. According to previous FCR studies for renewable energy,[1,46] we assume a range of ±20% in our pessimistic and optimistic cases. The available exploitable hydropower potential is also sensitive to the intensity of exclusion of protected land as environmental restriction. We evaluate the sensitivity of exploitable potential at different costs by adding a more strict case with 10% protected land excluded and a more tolerant case with 50% protected land excluded.

Hydropower potential has the highest sensitivity to stream flow at the global and country levels, and the sensitivity increases with the cut-off cost (Fig. 12). The importance of stream flow for electricity generation from hydropower is straightforward. It influences not only technical hydropower potential, but also design capacity, and therefore generation cost. It can alter the available hydropower potential by more than 30%, at 9 cents per kW h. The sensitivity of hydropower to stream flow shows a consistent pattern across countries.

The sensitivity of hydropower potential to efficiency is also high, and the sensitivity increases with the cut-off cost (Fig. 12). It influences hydropower potential differently in the pessimistic and optimistic cases because of the efficiency assumption. We are conservative in terms of the possible range of efficiency. This speaks to the importance of having a strong understanding of the biases present in the existing stream flow data contrast to our better understanding of efficiency in reality. The sensitivity of hydropower to efficiency also shows a consistent pattern across countries.

Table 2 Input parameter ranges used for the sensitivity analysis

Parameter	Units	Pessimistic	Central	Optimistic
Design flow	$m^3\ s^{-1}$	$Q_{40}{}^a$	Q_{30}	$Q_{20}{}^a$
Cost	—	$(1 + \delta_{67\%,UB}) \times$ central case	Central in Table 1	$(1 - \delta_{67\%,LB}) \times$ central case
η	—	0.5	0.80	0.95
Stream flow	$m^3\ s^{-1}$	0.7 × central case	Central	1.3 × central case
FCR	—	0.156	0.13	0.104
Protected land	—	10%	20%	50%

[a] Q_{40} and Q_{20} are the 40% and 20% monthly stream flow exceedance quantile.

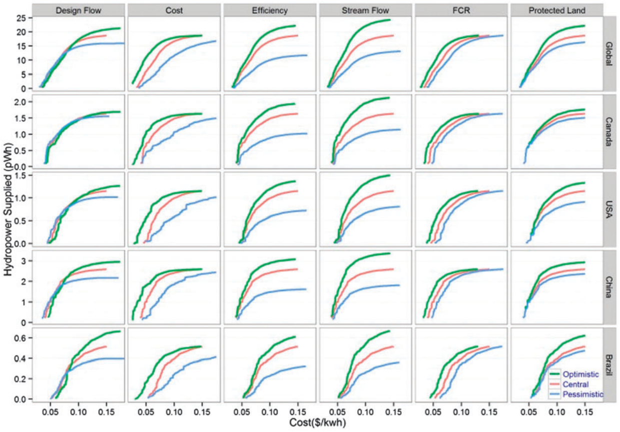

Fig. 12 Sensitivity of hydropower potential to six parameters for global and top four countries.

The impact of cost assumptions on hydropower potential estimation is different from other parameters. The low and high cost assumptions shift the cost-supply curves of hydropower potential. Cost assumptions alter hydropower potential globally by about 10% more in the optimistic case and about 30% less in the pessimistic case at a cost of 9 cents per kW h. The sensitivity of hydropower potential to cost assumptions increases with the cut-off cost in the pessimistic case, and decreases in the optimistic case. This indicates that the uncertainty from cost assumptions becomes important when we begin to explore the middle-cost hydropower resource in a pessimistic world.

The next tier of parameters are the FCR and protected land, which have smaller impacts compared to cost assumptions, but still potentially altering hydropower potential by more than 10%, at 9 cents per kW h. The impact of FCR is consistent across countries. However, the impact of protected land varies with countries, for example in United States and Brazil. The sensitivities of hydropower potential to the FCR and protected land show different patterns when varying cut-off cost. The protected land becomes more important when the cut-off cost increases. The FCR plays a more important role in hydropower availability in the low cost. This is of particular importance in hydropower development since low cost energy resources will generally be the first used.

Hydropower potential has the smallest sensitivity to design flow at the global and country levels because design with low exceedance quantile in the optimistic case, on the one hand, can obtain more hydropower, on the other hand, will increase the total cost due to larger design capacity, compared to the central case. The design flow can change the available hydropower potential by less than 8% at a cut-off cost of 0.09$ per kW h, and the difference is even smaller when we reduce the cut-off cost. This indicates that design flow can only become important for hydropower when we begin to explore the high-cost energy resource. This sensitivity of design flow is also different across countries though it is small. For example, the sensitivity of design flow to hydropower potential is much lower in Canada compared to other countries.

3.4. Evaluation

In order to put the results from this work into context, we first compare four types of hydropower potential with other global estimates (Table 3). These global estimates vary because of definitions of hydropower potential and employed methods. Hydropower potential estimation from Bartle[24] is technically feasible potential. Their estimation is generally lower than our estimate, and this difference varies by region. Hydropower potential from Labriet, *et al.*[23] and Pkehrel, *et al.*[21] is a gross potential. Our estimate is overall higher than their estimate,

Table 3 Comparison of four types of hydropower potential from this study with other estimates and electricity demand in 2005

	Gross				Technical		Economic	Exploitable	2005 Electricity generation	
Tw h per year	This study	Labriet *et al.* (2013)	Pokhrel *et al.* (2008)	WEC (2010)	This study	Bartle (2010)	This study	This study	All electricity	Hydro-electricity
Africa	22 585	9314	8758	3909	4491	1750	3562	2920	560	90
Asia	51 701	36 854	21 986	17 308	11 872	6800	10 025	7436	7299	952
Europe	3758	3702	4170	4919	1368	1140	1213	700	3743	567
Latin /South America[a]	27 958	13 050	10 492	7541	6257	2968	2344	1244	1176	649
North America	18 947	15 443	11 081	5511	6130	1510	3762	2899	4749	636
Oceania	2620	387	1986	654	353	200	239	151	266	39

[a] Latin America in this study and Bartle;[24] South America in other studies.

and the largest difference between our and their estimate, in Africa, is about 2 times. Hydropower potential estimation from WEC[22] is also a gross theoretical potential, but much lower in most regions except for Europe compared to gross potential in other three studies. For example, the gross hydropower potential estimated from this study is about six times of their study in Africa, while the difference is about one quarter in Europe.

There are several factors contributing to the difference between each estimate, even for the same type of hydropower potential. The most important factor contributing to the difference is the data, such as runoff, used in the calculation of gross hydropower potential. It can be one of the causes of the hydropower difference between the studies of Labriet, *et al.*[23] and Pkehrel, *et al.*[21] who used a similar method. Compared to head, the uncertainty from runoff in gross hydropower potential estimation is higher, especially at the regional and local scales. The contribution of uncertainty from runoff can be more important where head is large. A small change in runoff can result in large variation in hydropower potential given in the presence of a high head estimate.

It is reasonable that the technical, economic, and exploitable potentials of hydropower estimated in this study are lower than the gross or theoretical potentials from other studies. This is a first attempt to produce a consistent estimate for global economic and exploitable potential hydroelectric power potential. It will be helpful for evaluation of the economic and exploitable hydropower potential by comparing to other studies when they become available globally.

It is worth noting that our estimation of economic hydropower potential can be optimistic in that it includes limited consideration of specific factors such as, topography, geology and geomorphology that might make hydropower development infeasible or too costly in some specific locations. In addition, while our algorithm for calculating generation cost implicitly accounts for the cost of mitigation such as recreation and wildlife, there could be specific sites, that are not in the protected area database, where these or other factors preclude hydropower development.

We note that some existing plants use older, less efficient technologies while our estimate assumes the use of modern equipment. This means that our estimate represents a case where all current plants are repowered with new generation systems. This will tend to result in actual generation being smaller than the resource estimate.

It is useful to compare these four types of hydropower potential to total electricity generation and hydroelectricity generation in 2005. As we discussed, hydropower potential shows large variability across regions (Table 3). In Africa, Asia, North America and South America, the exploitable hydropower potential is a substantial portion of current electricity demand, though only a small fraction of hydropower potential has been developed for electricity generation in these regions. In contrast hydropower potential in Europe is relatively low, compared to electricity demand in the year 2005, and approximately 80% of potential was developed for electricity generation. In rapidly developing regions, such as Africa and South America, hydropower has the potential to meet a large portion of future demand and could play an even more important role in future energy systems.

We can conduct a more detailed comparison for the United States, where actual hydropower generation is compared to these new estimates at the FERC regional level (Fig. 10). The exploitable potential is about 1.5–4 times of current hydroelectricity generation across the FERC regions. While our hydro potential for the Portland FERC region is comparable to a more spatially detailed study,[8] which helps confirm our overall spatial methodology. Both studies, however, find hydro potential that is about three times current generation in this region.

One factor in potential overestimation is the implicit inclusion in our methodology of smaller hydropower sites that may not be feasible in reality. The detailed study for the Pacific Northwest[8] found that 26% of total potential capacity was either at a site with less than 1 MW of potential capacity or was a small hydro site (>1 MW but <50 MW capacity) that was infeasible due to unrealistically large impoundment size, dam height or length. These factors could potentially be included by using a much higher resolution analysis, but do not appear to be the major cause of differences between actual generation and estimated capacity. Overall, more detailed comparisons between hydro potential and actual practice would help refine estimates.

4. Conclusions

This study provides a comprehensive view of hydropower potential (gross, technical, economic, and exploitable) at spatial scales ranging from a 0.5 × 0.5 degree grid to global totals. Estimates of economic and exploitable potential depend on the price of power. At costs below 9 cents per kW h global exploitable hydropower potential is 16 pW h per year (1.8 TW), which is approximately equal to total world electricity demand in 2005 (15.7 pW h). Because hydroelectric power can be dispatched to help match supply and demand for power over short time scales, it can play an important complementary role in combination with other renewable resources, such as wind, whose generation is more variable.[1]

Uncertainty in estimates of hydropower potential can be traced to underlying factors such as estimates of stream flow. Improved estimates for stream flow and other information such as design-capacity, cost and finance would directly improve our estimates of hydropower potential.

All four types of hydropower potentials show large regional variation. Spatial patterns of gross hydropower potential are primarily dependent on elevation and precipitation, while economic hydropower potential is subject to additional factors such as stream flow magnitude and its variability. Environmental constraints, such as protected area exclusions, can also change the spatial pattern of exploitable hydropower potential. As a result of its heterogeneous spatial availability, cost, and electricity demand, hydropower plays different roles from country to country. In some countries such as DRC, hydropower potential is more than sufficient (>10 times) to meet total electricity demand, while in other countries such as

United Kingdom, hydropower potential can only meet a small portion (<3%) of total electricity demand.

These results have important policy implications because many of the factors that impact the exploitable potential of hydropower generation are influenced by policy choices. Policies to lower the cost of renewable generation through changes in financing and accounting rules and to protect valuable resource can change the economic and exploitable hydropower generation. This spatially resolved hydropower potential information can also help policy-makers gain insight into potential hydropower development together with consideration of regional energy demand.

As an evaluation of hydropower potential at the global level, there are several major caveats that attend our estimates. First, the parameters used in the estimation of each type of hydropower potential are the same across countries. Although, this helps us to obtain a consistent evaluation of the global hydropower potential and to make comparisons across regions and nations, in reality these parameters may vary spatially. For example, cost and finance will likely differ by country, and these differences can alter the estimation of available hydropower potential. Second, in terms of environmental restrictions, we use the data of urban extent and protected land from WDPA, the only available global data product. The estimation of hydropower in this study could be optimistic because the method doesn't completely capture constraints on the realizable potential due to data limitations and other factors, such as dams for multi-purposes, geology or soil characteristics for dam construction,[47] societal preferences,[47,48] legal/geopolitical concerns,[49] or minimum stream flow requirements.[49] For example, dams were built for other purposes such as flood control and recreation as well as hydro-electricity, and only about one-fifth of world dams were built for hydro-electricity. These potential restrictions should be addressed in the estimation of hydropower potential in future research when these data become available globally. Although our method can address these environmental concerns to some extent by considering the mitigation cost, a more comprehensive global product of environmental restrictions will help improve the hydropower potential estimation, especially at the regional or local levels for the purpose of hydropower development. Third, generation costs of hydropower electricity could be underestimated with limited consideration of some impacting factors such as, topography, geology and geomorphology, due to data limitations. The development of global datasets that estimate the impact of these additional factors remains an important research topic.

It is anticipated that future climate change will alter spatial and temporal magnitudes of evaporation and precipitation.[50,51] These changes will modify runoff and stream flow, and therefore, all types of hydropower potential. For example, Bartos and Chester[52] found that climate change may reduce average summertime generating capacity by 1.1–3.0% and up to 7.2–8.8% under a ten-year drought for vulnerable power stations in the Western United States, while Hamududu and Killingtveit[53] indicated that hydropower generation will change very little by 2050 under climate change based on country level analysis. Therefore, we suggest that further research intended to inform hydropower related policy-making needs to consider future hydropower potential under climate change based on fine resolution analysis (*e.g.* grid or basin levels), which will influence the long-term role of hydropower in future energy systems. The methods we have demonstrated in this paper will help evaluate the impact of climate change on hydropower potential at a wide range of spatial scales.

Appendix: modified representation of the river transport model

Similar as Swenson *et al.*,[31] the RTM routes water from one grid cell to its immediate downstream grid cell with a linear advection formula as below.

$$Q_{\text{out}} = \frac{V}{L}W \tag{A1}$$

where V is the effective local channel velocity (m s^{-1}), L is the effective flow distance from current grid cell to the downstream grid cell (m), and W is the river water storage in the local grid cell (m^3). The effective local channel velocity values are derived by averaging the channel velocity simulations from Li *et al.*,[30] *i.e.*, for each grid cell, the channel velocity value is the average of the hourly velocity time series produced by Li *et al.*[32] in the period of 1949–2004. The flow distance values are derived by Wu *et al.*[54] accounting for the curvature of real channel and thus much more realistic than those used by Swenson *et al.*[32] where the flow distance is estimated as the length of a straight line connecting the centers of two neighboring grid cells.

The change of channel water storage, W, is thus given by

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \sum Q_{\text{in}} - Q_{\text{out}} + R \tag{A2}$$

where $\sum Q_{\text{in}}$ is the sum of inflows from neighboring upstream grid cells (m^3 s^{-1}), Q_{out} is the outflow leaving the grid cell to its neighboring downstream grid cell (m^3 s^{-1}) as estimated by eqn (A1), and R is the volume of total runoff generated within the grid cell.

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Notes and references

1 Y. Zhou, P. Luckow, S. J. Smith and L. Clarke, *Environ. Sci. Technol.*, 2012, **46**, 7857–7864.
2 B. Wicke, E. Smeets, V. Dornburg, B. Vashev, T. Gaiser, W. Turkenburg and A. Faaij, *Energy Environ. Sci.*, 2011, **4**, 2669–2681.

3 B. Müller, W. Arlt and P. Wasserscheid, *Energy Environ. Sci.*, 2011, **4**, 4322–4331.

4 A. Kumar, T. Schei, A. Ahenkorah, R. C. Rodriguez, J.-M. Devernay, M. Freitas, D. Hall, Å. Killingtveit and Z. Liu, in *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, ed. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer and C. von Stechow, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2011.

5 Y. Zhou, L. Clarke and J. Eom, *et al.*, *Appl. Energy*, 2014, **113**, 1077–1088.

6 S. H. Kim, J. Edmonds, J. Lurz, S. J. Smith and M. Wise, *Energy J.*, 2006, 63–91.

7 J. Edmonds, J. Clarke, J. Dooley, S. H. Kim and S. J. Smith, *Energy Econ.*, 2004, **26**, 517–537.

8 D. G. Hall, K. L. Verdin and R. D. Lee, Prepared for the US Department of Energy. Idaho: Idaho National Laboratory, available from www. inl. gov/technicalpublications/Documents/53941, 2012.

9 B. Kusre, D. Baruah, P. Bordoloi and S. Patra, *Appl. Energy*, 2010, **87**, 298–309.

10 L. Kosnik, *Energy Policy*, 2010, **38**, 5512–5519.

11 A. Demirbaş and R. Bakış, *Energy Explor. Exploit.*, 2003, **21**, 405–414.

12 J.-F. Cyr, M. Landry and Y. Gagnon, *Renewable Energy*, 2011, **36**, 2940–2950.

13 X. Chang, X. Liu and W. Zhou, *Energy*, 2010, **35**, 4400–4406.

14 W. Liu, H. Lund, B. V. Mathiesen and X. Zhang, *Appl. Energy*, 2011, **88**, 518–525.

15 S. Cherry, K. S. Reeves, R. D. Lee, G. R. Carroll, G. L. Sommers and K. L. Verdin, *Water energy resources of the United States with emphasis on low head/low power resources*, Idaho National Engineering and Environmental Laboratory, 2004.

16 B. Lehner, G. Czisch and S. Vassolo, *Energy Policy*, 2005, **33**, 839–855.

17 C. Koç, *Renewable Sustainable Energy Rev.*, 2014, **39**, 498–508.

18 R. E. Sims, R. N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H. Nimir, B. Schlamadinger, J. Torres-Martínez and C. Turner, *Clim. Change*, 2007, 251–322.

19 G. Resch, A. Held, T. Faber, C. Panzer, F. Toro and R. Haas, *Energy Policy*, 2008, **36**, 4048–4056.

20 K. Tomabechi, *Energies*, 2010, **3**, 686–695.

21 Y. N. Pokhrel, T. Oki and S. Kanae, Annual Journal of Hydraulic Engineering, *J. Corros. Sci. Eng.*, 2008, **52**, 7–12.

22 WEC, World Energy Council, 2010.

23 M. Labriet, A. Kanudia, R. Loulou, M. Biberacher, N. Edwards, P. Holden, B. P. OU, S. J. Ram, M. Vielle and J. Dietrich, *Uncertainty analyses in TIAM, ERMITAGE WP8 – Climate and Energy/Technology Deliverable 8.1*, 2013.

24 A. Bartle, *Hydropower and Dams, World Atlas*, Aqua Media International Ltd, Sutton, UK, 2010.

25 P. Moriarty and D. Honnery, *Renewable Sustainable Energy Rev.*, 2012, **16**, 244–252.

26 V. V. Klimenko, A. G. Tereshin and O. V. Mikushina, *Russ. J. Gen. Chem.*, 2009, **79**, 2469–2476.

27 M. Hejazi, J. Edmonds, L. Clarke, P. Kyle, E. Davies, V. Chaturvedi, M. Wise, P. Patel, J. Eom and K. Calvin, *Hydrol. Earth Syst. Sci.*, 2014, **18**, 2859–2883.

28 T. D. Mitchell and P. D. Jones, *Int. J. Bioclimatol. Biometeorol.*, 2005, **25**, 693–712.

29 T. D. Mitchell, T. R. Carter, P. D. Jones, M. Hulme and M. New, *Tyndall Centre for Climate Change Research Working Paper*, 2004, **55**, 25.

30 H. Li, M. S. Wigmosta, H. Wu, M. Huang, Y. Ke, A. M. Coleman and L. R. Leung, *Journal of Hydrometeorology*, 2013, **14**, 808–828.

31 S. Swenson, D. Lawrence and H. Lee, *Journal of Advances in Modeling Earth Systems*, 2012, 4.

32 H.-Y. Li, L. R. Leung, A. Getirana, M. Huang, H. Wu, Y. Xu, J. Guo and N. Voisin, *Journal of Hydrometeorology*, 2015, **16**, 948–971.

33 B. Lehner, K. Verdin and A. Jarvis, *Trans., Am. Geophys. Union*, 2008, **89**, 93–94.

34 Eurelectric, Study on the importance of harnessing the hydropower resources of the world, Union of the Electric Industry (Eurelectric), Hydro Power and other Renewable Energies Study Committee, Brussels, 1997.

35 B. Lehner, G. Czisch and S. Vassolo, *EuroWasser: Model-based Assessment of European Water Resources and Hydrology in the Face of Global Change*, Kassel, 2001, ch. 8.

36 S.-C. Kao, *An Assessment of Energy Potential from New Stream-reach Development in the United States*, Oak Ridge National Laboratory, 2013.

37 U.S. Bureau of Reclamation, *Hydropower Resource Assessment at Existing Reclamation Facilities*, Denver, CO, 2011.

38 D. G. Hall, R. T. Hunt, K. S. Reeves and G. R. Carroll, *Estimation of Economic Parameters of US Hydropower Resources*, 2003.

39 Y. Zhou, S. J. Smith, C. D. Elvidge, K. Zhao, A. Thomson and M. Imhoff, *Remote Sens. Environ.*, 2014, **147**, 173–185.

40 Y. Zhou, S. J. Smith, K. Zhao, M. Imhoff, A. Thomson, B. Bond-Lamberty, G. R. Asrar, X. Zhang, C. He and C. D. Elvidge, *Environ. Res. Lett.*, 2015, **10**, 054011.

41 U.S. Energy Information Administration (EIA), US Energy and Information Administration, Washington, DC, available at http://www.eia.gov/, 2015.

42 Integrated Assessment Modeling Consortium, 2014, DOI: https://secure.iiasa.ac.at/web-apps/ene/AR5DB/.

43 EURELECTRIC, Efficiency in Electricity Generation, 2003.

44 J. Gordon, *Can. J. Civ. Eng.*, 2001, **28**, 238–253.

45 O. Paish, *Renewable Sustainable Energy Rev.*, 2002, **6**, 537–556.

46 Y. Zhang and S. Smith, PNNL-16727, 2007.

47 T. E. Thórhallsdóttir, *Environ. Impact Assess. Rev.*, 2007, **27**, 545–568.

48 Š. Bojnec and D. Papler, *Agric. Econ.*, 2011, **57**, 484–492.

49 K. Bakker, *Polit. Geogr.*, 1999, **18**, 209–232.

50 R. Chadwick, I. Boutle and G. Martin, *J. Clim.*, 2012, **26**, 3803–3822.

51 C. Chou, J. D. Neelin, C.-A. Chen and J.-Y. Tu, *J. Clim.*, 2009, **22**, 1982–2005.

52 M. D. Bartos and M. V. Chester, *Nat. Clim. Change*, 2015, DOI: 10.1038/nclimate2648.

53 B. Hamududu and A. Killingtveit, *Energies*, 2012, **5**, 305–322.

54 H. Wu, J. S. Kimball, H. Li, M. Huang, L. R. Leung and R. F. Adler, *Water Resour. Res.*, 2012, 48.