

Global riverine theoretical hydrokinetic resource assessment

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ARTICLE INFO

Article history:

Received 10 September 2020

Received in revised form

17 March 2021

Accepted 21 April 2021

Available online 27 April 2021

Keywords:

Hydrokinetic

Resource assessment

Hydropower

Energy poverty

Global assessment

Renewable energy

ABSTRACT

Hydrokinetic energy conversion refers to the conversion of kinetic energy in moving water to electricity. It offers an alternative to conventional hydropower, with benefits of modularity and scalability, in addition to being environmentally and socially less impactful. This study aims to determine the theoretical global riverine hydrokinetic resource. We use a 35 year modelled daily discharge data set and vectorised representation of rivers, with near-global coverage and suitable spatiotemporal resolution, to determine the mean annual energy yield of 2.94 million river reaches. The mean global resource (excluding Greenland) is estimated to be $58\,400 \pm 109$ TWh yr⁻¹ (6.660 ± 0.012 TW). Consideration of global spatial distribution, by river reach, illustrates regional variation and shows a tendency for potential to be concentrated along major rivers and in areas of significant elevation change. China, Russia and Brazil are found to be the countries with the greatest potential. After normalisation by total river length, Bhutan, Nepal and Tajikistan also show great potential. Hydrokinetic energy conversion can benefit isolated communities currently without access to electricity. We consider how the specific advantages of this particular technology have the potential to be combined with and complement other established forms of renewable energy technology, providing the means to support the reduction of energy poverty.

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1. Introduction

Energy poverty has been defined by the International Energy Agency (IEA) as a lack of access to electricity and clean cooking facilities [1]. Access to electricity provides positive socio-economic impacts for disadvantaged, isolated communities, in developing nations [2,3]. This access can be improved by grid-extension, the use of diesel generators, or small-scale renewable energy (RE) systems. Grid-extension can be slow to help these communities due to low consumption and poor capacity factors causing utility companies to view such endeavours as uneconomic [4–6]. The capacity factor is a measure of actual power output relative to potential power output. It is not just a measure of efficiency, since it can be affected by variations in demand. For example, a period of high output coinciding with low demand will see a fall in capacity factor, causing an increase in the levelised cost of electricity (LCOE). LCOE provides a means for comparing the unit costs of different technologies over the period of their operation and is defined as the

ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent. For example, the units used might be \$/kWh, or \$/MWh. Running diesel generators is challenging for isolated communities due to high LCOE rates, rising diesel prices, the constant requirement for fuel and associated transportation difficulties. RE technologies use energy obtained from the continuous or repetitive currents of energy recurring in the natural environment to provide a conversion to electrical energy [7]. Water is one such source of energy, expressed as the propagation of gravity waves; the existence of temperature gradients; in the gravitational potential energy attained through increased elevation; and, in the movement of the fluid itself. The latter two examples are most relevant in a riverine context and the conversion of these forms of energy can be described as a hydrostatic or a hydrokinetic approach, respectively. The hydrostatic approach is found in the conventional hydropower method of impounding a store of gravitational potential energy as a hydraulic head behind the construction of a dam. The conversion to electrical energy is as a result of the conversion of gravitational potential energy into kinetic energy, which is used to drive the rotation of a hydraulic turbine. The hydrokinetic approach involves converting the energy of the flowing water directly. Hydrokinetic energy

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conversion (HEC) refers to the conversion of the kinetic energy contained in river streams, tidal currents, or man-made waterways.

Conventional hydropower plants have proven effective in rural mountainous communities to provide access to electricity [8,9]. With a global installed capacity estimated to be 1.3 TW [10], hydropower accounted for 16.2% of global electricity production in 2018, generating more electricity than any other RE resource [11]. It is desirable for an energy source to be predictable, reliable and dispatchable [12]. Compared to other sources of RE (e.g. solar and wind), hydropower along with tidal power best demonstrate these characteristics. Despite providing large amounts of electricity, the development of hydropower has raised serious socio-economic and environmental concerns (e.g. displacement of indigenous people, deforestation, loss of habitats, flood risk, corruption, etc.) that question the justification for continued development [13–15]. Further, from a political, practical and economic perspective, future hydropower plant constructions may be either technically or economically infeasible [16,17]. As a specific example, Punys et al. [18] state that a limit on the growth of such plants, in Lithuania, has arisen due to environmental constraints, bans on the damming of rivers, the introduction of laws aimed at reducing the incentives offered for development of such projects and a change in administrative preferences towards less impactful RE technologies, including HEC. Ansar et al. [17] suggest that in most countries, future large-scale projects will be too costly in absolute terms. They emphasise that this is particularly the case for developing countries. If we also consider the increasing sensitivity to environmental impacts, which is most apparent in developed countries, we might conclude that this is a global issue, if not always for the same reasons. Though criticism is predominately directed at large-scale hydropower plants, Abbasi and Abbasi [19] point out that a move to the development of more mini- and micro-scale hydropower plants, as what they describe as a decentralisation of hydropower production, causes problems no less serious, when considered per kilowatt generated.

Advantages of HEC over hydropower include: modularity and scalability; less environmental and social impact; and ease of construction due to being lower cost, quicker to construct and requiring less planning consent [18,20,21]. While HEC cannot compete with conventional hydropower, in terms of LCOE [22], it can compete in absolute terms. Thus the bar is lowered for communities without access to electricity, yet living close to running water. In this situation, HEC offers a cost-effective solution for moving beyond having no electricity to the life-changing scenario of having some electricity. In addition to extending access to electricity for isolated communities, HEC constructively benefits the current desire to transition away from fossil fuel based energy resources that contribute to greenhouse gas emissions. HEC can be a significant contributor to a portfolio of RE technologies used by communities directly, or via a grid, since energy from HEC is largely predictable, reliable and dispatchable [21,23]. The dynamics of tidal currents are well understood and variations in river flow tend to be seasonal, or due to episodic events. With the exception of particularly flashy catchments, river discharge flows continuously over a given day, or a series of days. Changes to the flow tend to be more gradual, as the seasons change. For this reason, HEC can often be considered a baseload power source. Reducing intermittency and unpredictability means that power is made accessible for critical applications, such as refrigeration, or medical care. This may profoundly benefit communities currently without reliable power. Communities relying on diesel generators can reduce their fuel costs, or even eliminate them, by combining solar and/or wind power with HEC.

The main challenges to developing HEC technology are: reducing the LCOE; optimising turbine performance and

deployment in arrays; balancing energy extraction with environmental impact; addressing socio-economic concerns; and resource assessment to determine annual energy yield and analysis of site characteristics [20,24]. Site selection, for the deployment of RE technology, is usually determined by an assessment of a resource according to three perspectives: theoretical, technical and practical. A theoretical resource assessment is a determination of the total annual energy that is hypothetically available, without consideration of extraction. A technical resource assessment calculates the portion of the theoretical amount of energy that can be converted into electricity, by the technology of interest. A practical resource assessment assesses other considerations and constraints, including economic, social, environmental and regulatory. A detailed study is required to estimate the practical resource, since relevant factors here can be broad, overlapping and open to interpretation. The suitability of a HEC site depends upon a number of factors, such as fluid dynamics, river/seabed geometry and the stability of high-velocity zones. In rivers, HEC devices are ideally located at locations with relatively steady flow throughout the year, that are not prone to serious flood events, too much turbulence, or extended periods of low water level or flow velocity. Varying velocities and water levels mean that the data needed for an assessment of a HEC site is highly site-specific [25]. Previous large-scale HEC resource assessments have mainly been performed for tidal streams [26–28]. A notable large-scale riverine hydrokinetic resource assessment, considering the continental United States of America, determined that there was a theoretical resource of 1381 TWh yr⁻¹ [29]. Despite this study being a theoretical resource assessment, the authors used a discharge restriction to exclude reaches which were clearly unfeasible for HEC deployment. It could be argued that this causes the distinction between a theoretical and technical resource assessment to be blurred somewhat and that such restrictions might be best left to a purely technical resource assessment. Similar restrictions were applied in an earlier study for the United States, which claimed to be a technical resource assessment, providing an estimate of 110 TWh yr⁻¹ [30]. Thus, large-scale riverine assessments are few and a global riverine HEC resource assessment is lacking.

A better understanding of rivers at the continental- and global-scale has followed from studies that have used remote sensing data: to trace river networks [31–33]; extract basin and floodplain parameters and features [34,35]; map the extent of flooding and flood risk [36–38]; estimate discharge [39–41]; estimate river channel parameters [32,42,43]; and describe the relationship between width, slope catchment area, meander wavelength, sinuosity and discharge [44]. Such studies have contributed to the creation of data sets describing these features at a large-scale. To understand natural river flow requires an understanding of the complex, spatiotemporal fluctuations of a number of variables. This implies an acceptance of reduced resolution as scale increases. The usefulness of global river databases for the purpose of large-scale hydrokinetic resource assessment has been questioned by some, highlighting the need for a development of methods for database analysis [20,25].

HEC is relatively immature when compared with other RE technologies. Its development can be assisted by the determination of the theoretical global riverine hydrokinetic resource and an identification of the locations offering the most potential for further, site-specific resource assessment. The aim of this study is to provide a macroscopic perspective of the potential for HEC, with the objective of supporting a technology that can help reduce energy poverty. We hypothesise that there is a significant, under-utilised resource available for the benefit of disadvantaged, isolated communities. This study uses a riverine data set of modelled daily discharge between 1979 and 2013, with near-global coverage.

2. Methodology

2.1. Theoretical hydrokinetic resource assessment

A theoretical hydrokinetic resource assessment of global rivers was undertaken using the standard hydrological engineering formula for determination of theoretical hydraulic power

$$P = \gamma QH \quad (1)$$

where γ is the specific weight of water (9800 N m^{-3}), Q is discharge and H is the change in elevation of the river reach considered. This equation is derived from a consideration of gravitational potential energy

$$U_g = mgH \quad (2)$$

where m is the mass of water and g is the acceleration due to gravity. Since m is the product of density ρ and volume V

$$U_g = \rho VgH \quad (3)$$

Power is the rate of energy conversion and discharge is the volumetric flow rate. Therefore, dividing by time t gives

$$P = \rho QgH \quad (4)$$

Given that specific weight $\gamma = \rho g$, this provides the derivation of Eq. (1).

An alternative method for determining the theoretical power of water flowing through a cross-section would be to use

$$P = \frac{1}{2} \rho A v^3 \quad (5)$$

where A is the cross-sectional area and v is the flow velocity. This equation is derived from kinetic energy and is therefore arguably more appropriate for assessing a hydrokinetic resource. With this approach, knowledge of river width w and depth d is required to calculate A , in addition to knowing v . The Manning formula can be used to calculate v with

$$v = \frac{R^{2/3} s^{1/2}}{n} \quad (6)$$

where R is the hydraulic radius, s is the slope and n is the Manning roughness coefficient. Relatively limited empirical information on river channel form is available at a continental-scale [32] and v is highly variable in time and space [45]. A data set, of sufficient temporal and spatial resolution, for Q and H is provided by the Global Reach-level A priori Discharge Estimates for Surface Water and Ocean Topography (GRADES) [46].

2.2. Data

GRADES is a 35 year reconstructed record of daily values for Q , from the beginning of 1979 to the end of 2013, that incorporates the Variable Infiltration Capacity (VIC) land surface model (LSM) [47] and the Routing Application for Parallel computation of Discharge (RAPID) flow routing model [48,49]. Vectorisation of the river network and separation of the individual catchments was achieved using the Multi-Error-Removed-Improved-Terrain (MERIT) Hydro global hydrography data set, which provides high-resolution, vectorised, global flow direction maps at 3-arc sec resolution ($\sim 90 \text{ m}$ at the equator) [33]. MERIT Hydro is based on a high-accuracy global digital elevation model (DEM), known as MERIT DEM [50]. An advantage that this global hydrography data set has over

preexisting data sets [51,52], in addition to the more realistic depiction of river flowlines, is coverage above 60°N . The GRADES data set includes additional information for each river reach, including H , length L and slope s .

To use MERIT Hydro in GRADES, the data set was first separated into basins, as defined within HydroBASINS. This is a subset of the HydroSHEDS DEM [53], that provides a series of polygon layers depicting watersheds, as basins and sub-basins, at a global scale [31]. Lin et al. [46] found that the basin boundaries defined by MERIT Hydro and HydroBASINS differed globally by $<1\%$. Verdin and Verdin [54] developed the Pfafstetter system to delineate and code hierarchically nested catchments, using a simple coding system that enables the description of stream network position without need of a graphical information system (GIS). In this system, there are 9 continental-level divisions, which are defined as Level 1 basins (Fig. 1). Further division of each continental-level basin into 9 large sub-units provides Level 2 basins. This process continues down to Level 12. The process to merge the HydroSHEDS definition of basin boundaries to MERIT Hydro involved first identifying 61 Level 2 basins, before being grouped into Level 1 continental-levels. The median (mean) length of each river reach in the data set is 6.8 km (9.2 km).

The atmospheric forcing which contributes to the LSM is from a 0.1° and 3-hourly precipitation data set [55]. Parameter calibration and bias calibration for the LSM was performed against machine learning derived global runoff characteristic maps [56]. There is an increasing recognition that machine learning is a powerful approach to understanding hydrology in ungauged basins [46,57].

Flow routing (also referred to as flood routing) predicts the downstream hydrograph that results from an upstream hydrograph. Generally, a hydrograph downstream will show attenuation and a time delay. This can be considered from hydrologic, or hydraulic, principles. The former is concerned with the conservation of mass and the latter with conservation of momentum and energy.

If considering a single reach river and regarding the channel as a linear store, the continuity equation expresses the rate of change in storage S , as the difference between the input I and the output O from the reach

$$\frac{dS}{dt} = I(t) - O(t) \quad (7)$$

Given that the aim is to gain knowledge of the downstream hydrograph, the problem consists of finding $O(t)$, given $I(t)$ and suitable assumptions about the form of S . The Muskingum-Cunge method [58], applies this continuity equation at time t_1 and t_2 , aiming to determine $O(t_2)$ using

$$O(t_2) = c_1 I(t_1) + c_2 I(t_2) + c_3 O(t_1) \quad \text{where } \sum c_i = 1 \quad (8)$$

The RAPID flow routing model provides flexibility in dealing with vector river networks in a range of regional-to continental-

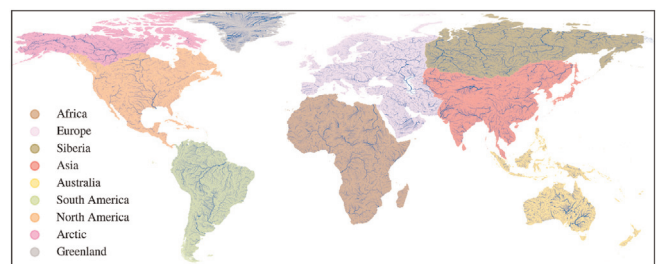


Fig. 1. Level 1 continental divisions used in HydroBASINS, as defined by the Pfafstetter coding system.

scale applications, as demonstrated in earlier studies [59–62]. Previous vector-based representations of river networks [31,48,63] provide realistic channel representations, but have only been applied regionally. GRADES builds upon these previous efforts by providing global coverage, using an unprecedented 2.94 million reaches. See the supplementary material for further discussion on how RAPID is implemented within GRADES.

Unfortunately, GRADES does not include data for the Greenland continental-level basin, at this time, due to a lack of sufficient training and validation data (M. Pan, coauthor of Lin et al. [46]; Pers. Comm.).

2.3. Calculating power and associated uncertainties

GRADES provides H and daily values of Q , from 1979 to 2013, for 2.94 million river reaches representative of the global river network, apart from Greenland. With this data expressed as a matrix \mathbf{Q} , a vector \vec{H} and using Eq. (1), a matrix \mathbf{P} representing values for P over m days and for n river reaches can be written as

$$\mathbf{P} = \gamma \mathbf{Q} \circ (\vec{H} \cdot \vec{1}_m^T)^T \quad \text{where } \mathbf{P}, \mathbf{Q} \in \mathbb{R}^{m \times n} \text{ and } \vec{H} \in \mathbb{R}^n \quad (9)$$

A vector of m ones is represented by $\vec{1}_m$ and the operation \circ describes a Hadamard (element-wise) product. With \mathbf{P} we now have values that represent the theoretical conversion of gravitational potential energy to kinetic energy that occurs along each reach, for each day of the record.

A vector \vec{P} of daily values of P , representing temporal variation of total power in the area for which \mathbf{Q} and \vec{H} are relevant, is given by

$$\vec{P}_i = \sum_{j=1}^n P_{ij} \quad \text{where } \vec{P} \in \mathbb{R}^m \quad (10)$$

The mean total power \bar{P} of the area considered is given by

$$\bar{P} = \frac{1}{m} \sum_{i=1}^m \sum_{j=1}^n P_{ij} \quad \text{where } \bar{P} \in \mathbb{R} \quad (11)$$

with this calculation, we are effectively summing the power for n reaches on a given day (Eq. (10)) and then calculating the mean of m daily values. Therefore, this represents the collective power of all reaches of a continental-level basin, or globally, as a mean of all daily values within the period considered.

The uncertainty stated with the estimated value of the theoretical riverine hydrokinetic resource, globally and for each continental basin, is the standard error of the mean (SEM). This is calculated using

$$\text{SEM} = \frac{\sigma}{\sqrt{m}} \quad (12)$$

where the standard deviation σ is given by

$$\sigma = \sqrt{\frac{1}{m-1} \sum_{i=1}^m (\vec{P}_i - \bar{P})^2} \quad (13)$$

The uncertainty in daily values for power $\Delta \vec{P}$ requires consideration of the terms in Eq. (1). The uncertainty of γ has been assumed to be negligible and therefore not considered. The change in elevation of each river reach H is derived from the measurements of MERIT DEM. This model is based upon improvements to the

elevation measurements made by the Shuttle Radar Topography Mission (SRTM) of February 2000 [64]. These improvements increased the percentage of land areas mapped with a vertical accuracy of ± 2 m from 39% to 58% after the application of a global-scale algorithm to remove absolute bias, stripe noise, speckled noise and tree height bias [50]. In this study, a linear absolute error that holds for 90% of measurements (LE90) is stated as ± 5 m, with a suggestion that the accuracy of MERIT DEM is relatively low in mountainous areas, where sub-pixel topography variability is large. A more recent evaluation of the accuracy of MERIT DEM for floodplains provided a more favourable assessment, with mean error, mean absolute error and root mean square error of ± 1.09 m, ± 1.69 m and ± 2.32 m, respectively [65]. Given the global perspective of this resource assessment, the more conservative value of ± 5 m is assumed. Since the change in elevation is determined from measurements at either end of a river reach, an absolute error for H is given by

$$\Delta H = \sqrt{5^2 + 5^2} = 7 \text{ m} \quad (14)$$

The uncertainty in discharge Q is based upon an analysis of the accuracy of GRADES [46]. After evaluation of the modelled data against ~ 14 000 gauges, the authors report that 35% (64%) have a percent bias (PBIAS) within $\pm 20\%$ ($\pm 50\%$). PBIAS measures the average tendency of the modelled discharge Q_m to be greater or smaller than observed discharge Q_o

$$\text{PBIAS} = \frac{\overline{Q_m} - \overline{Q_o}}{\overline{Q_o}} \times 100\% \quad (15)$$

with an optimal value of PBIAS = 0% and low-magnitude values indicating accurate model simulation. It can be determined from the results published by Lin et al. [46] that $\sim 85\%$ of evaluated modelled data have a PBIAS $\leq \pm 100\%$, with a slight skew towards negative values, representative of an underestimation bias. The remaining $\sim 15\%$ have a PBIAS $> +100\%$, which is representative of an overestimation bias. For this study, the fractional error for Q is considered to be

$$\frac{\Delta Q}{Q} = 1 \quad (16)$$

where ΔQ represents the absolute error for Q . The absolute error for \vec{P} (Eq. (10)) is therefore given by

$$\Delta \vec{P} = \sqrt{\sum_{j=1}^n P_{ij} \left(\left(\frac{\Delta Q}{Q} \right)^2 + \left(\frac{\Delta H}{H_j} \right)^2 \right)^2} \quad (17)$$

Given Eq. (16), this can be simplified to

$$\Delta \vec{P} = \sqrt{\sum_{j=1}^n P_{ij} \left(1 + \left(\frac{\Delta H}{H_j} \right)^2 \right)^2} \quad (18)$$

and can be computed using data from GRADES with

$$\Delta \vec{P} = \left(\left(\gamma \left[\mathbf{Q} \circ (\vec{H} \cdot \vec{1}_m^T)^T \right] \right) \cdot \left(\vec{1}_n + \left((\Delta H \cdot \vec{1}_n) \oslash \vec{H} \right) \circ^2 \right) \right)^{\circ \frac{1}{2}} \quad (19)$$

where Hadamard (element-wise) operations for division and power are described using \oslash and \circ , respectively.

3. Results

3.1. Theoretical global riverine hydrokinetic resource

Global values for the theoretical riverine hydrokinetic resource were determined by summing the results of calculations on each continental-level basin (Fig. 1), excluding Greenland, for which data is unavailable in GRADES. Having calculated the theoretical riverine hydrokinetic resource for each continental-level basin (Fig. 2), the global resource (excluding Greenland) is estimated to be $58\,400 \pm 109 \text{ TWh yr}^{-1}$ (Eq. (11) and (12)).

Expressing a resource with units of TWh yr^{-1} describes the average annual energy yield, but since it is a measure of energy conversion over a given time it can also be considered the average annual power. It is instructive to consider how power varies daily over the period 1979–2013, globally (Fig. 3) and for each continental-level basin (Fig. 4). The mean power of global rivers \bar{P} over the period 1979–2013 can also be expressed as $6.660 \pm 0.012 \text{ TW}$.

A clear intra-annual oscillation of power is observed for \bar{P} (Figs. 3 and 4) and very pronounced for the continental-level basin of Asia. For all continental-level basins and globally, this oscillation of power is asymmetrical, with annual periods of maximum power being further from the average than for periods of annual minimum power. This is clearly seen in the box plots (Fig. 5). A least squares polynomial fit \hat{P} has been applied to determine the trend described within the oscillations. The potential range of this fit $\Delta\hat{P}$ was established by applying a least squares polynomial fit to the maximum and minimum values for \bar{P} , as calculated by Eq. (17) or Eq. (19), using the range of potential values for H (Eq. (14)) and Q (Eq. (16)).

A rising trend in inter-annual power of $1.49 \pm 138 \text{ MWh d}^{-1}$ is seen globally, with similar rising trends present for all continental-level basins. It must be noted that significant uncertainty in the gradient of \hat{P} , as determined by $\Delta\hat{P}$, means that the trend may be neutral or, for some continental-level basins, could be falling (Fig. 6). Again, with due regard given to the uncertainty, it is seen that the rising trend is most significant for Africa, Australia and South America. In contrast, Europe, North America and the Arctic

barely show a rising trend. This division would imply a difference between the Southern Hemisphere and the Northern Hemisphere.

The calculation of P is dependent upon the product of γ , Q and H (Eq. (1)). For each reach, γ and H are constant. Therefore, we can say that $P \propto Q$ and that any fluctuations in P are directly as a result of changes in Q . Reasons for this may be attributed to changes in factors such as rainfall, or the rate of snowmelt and icemelt. The visible intra-annual oscillation can be explained by the expected seasonal variations of these factors. Inter-annual change may be attributed to changes in these factors due to a change in the climate. The rate of snowmelt and icemelt would be expected to correlate with a rise in global temperature. A rising global temperature has been linked to an increase in the intensity of the hydrological cycle [66], but Held and Soden [67] advise against a simple assumption that global systems become more energetic as they warm and conclude that the complexity of such systems should guard against over-confidence in simple arguments. Studies that have investigated an asymmetry between the climate change effects and affects of the Northern and Southern Hemispheres may be relevant in exploring further the observed differences in our results [68–70].

The theoretical riverine hydrokinetic resource can be determined by river reach, thus permitting a representation of spatial distribution and identification of areas with high concentrations of hydrokinetic energy (Fig. 7). A general description of areas which are prominent, would include: the Himalayas, Tibetan Plateau and surrounding areas; the large, mountainous islands of Borneo, Indonesia and New Guinea; New Zealand; the Andes; the Pacific Northwest; Scandinavia; the Congo Basin and Equatorial Africa; Madagascar; and many of the major rivers of the world. This attempt to qualitatively describe areas of Earth identified as having potential for HEC, apart from including major rivers as might be expected, highlights the predominance of areas that have rivers with significant elevation change.

3.2. Distribution of hydrokinetic energy by country

The theoretical riverine hydrokinetic resource is considered by country (Fig. 8). The countries assessed to have the greatest total hydrokinetic resource are China, Russia and Brazil (Fig. 9).

Determining the theoretical riverine hydrokinetic resource by country is useful, but favours larger countries, which tend to have a

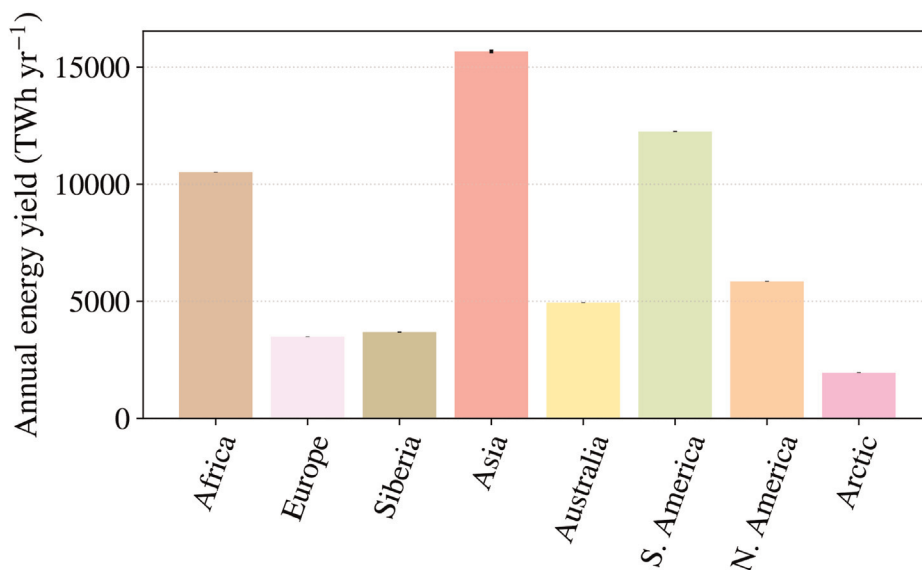


Fig. 2. Mean annual energy yield, by continental-level basin, averaged over the period 1979–2013.

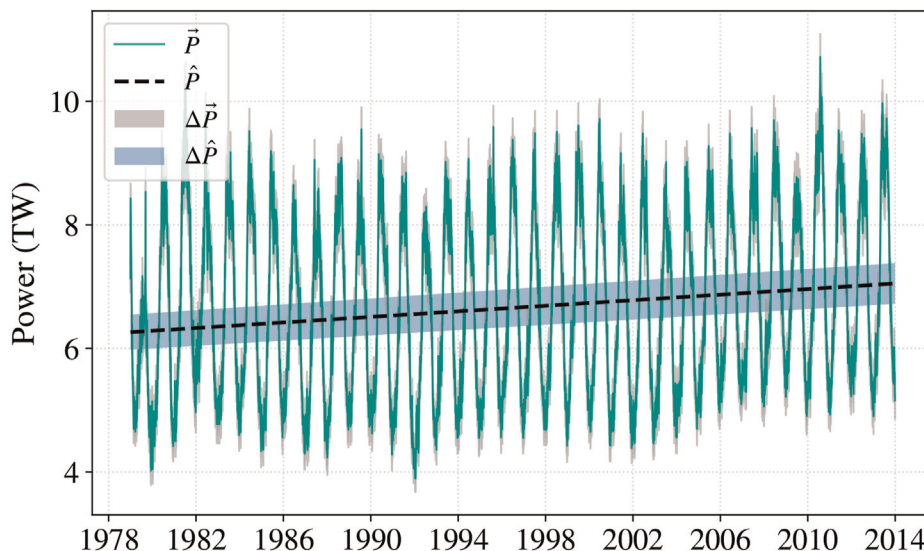


Fig. 3. Total daily power \hat{P} of global rivers (excluding Greenland) between 1979 and 2013, including the uncertainty in daily values $\Delta\hat{P}$, a least squares polynomial fit \hat{P} and corresponding uncertainty $\Delta\hat{P}$.

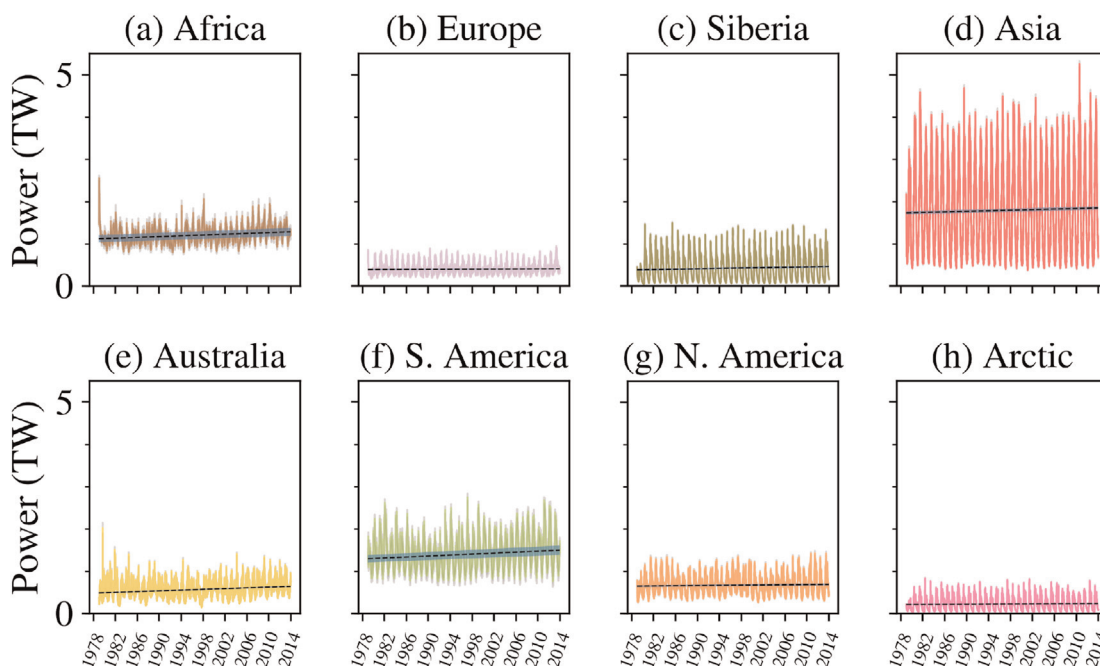


Fig. 4. Total daily power for each continental-level basin (excluding Greenland), between 1979 and 2013.

greater combined length of rivers. Therefore, it may be instructive to consider the resource relative to the total length of the rivers in a country, providing a normalised perspective, which is referred to here as annual energy yield density (Fig. 10). The river length of each river reach is also provided by GRADES, so the total length is a simple summation. In this case, the countries assessed to have the greatest total hydrokinetic resource, relative to total river length, are Bhutan, Nepal and Tajikistan (Fig. 11).

4. Discussion

This study uses a 35 year reconstructed record of daily discharge to provide an estimate of the theoretical global (excluding

Greenland) riverine hydrokinetic resource to be $58\,400 \pm 109$ TWh yr^{-1} , which is a mean power of 6.660 ± 0.012 TW. A representation of the global spatial distribution is presented, by individual river reach and grouped by country. The countries with the greatest potential for HEC overall are identified as China, Russia and Brazil. After normalisation by total river length, Bhutan, Nepal and Tajikistan are also shown to have great potential.

Though the uncertainty in the data for Q and H used within this study are significant, they may be deemed acceptable according to the stated aims. It is difficult to evaluate the accuracy of the estimates of power and annual energy yield that are calculated with this data, for 2.94 million individual river reaches. For this reason, the results presented here might be best considered a first-order

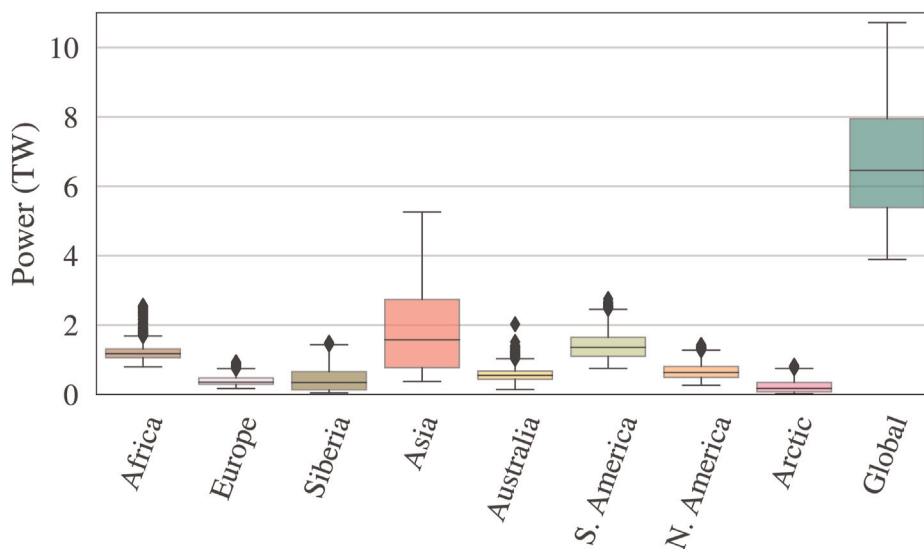


Fig. 5. Box plots for the total daily power for each continental-level basin (excluding Greenland) and globally, between 1979 and 2013.

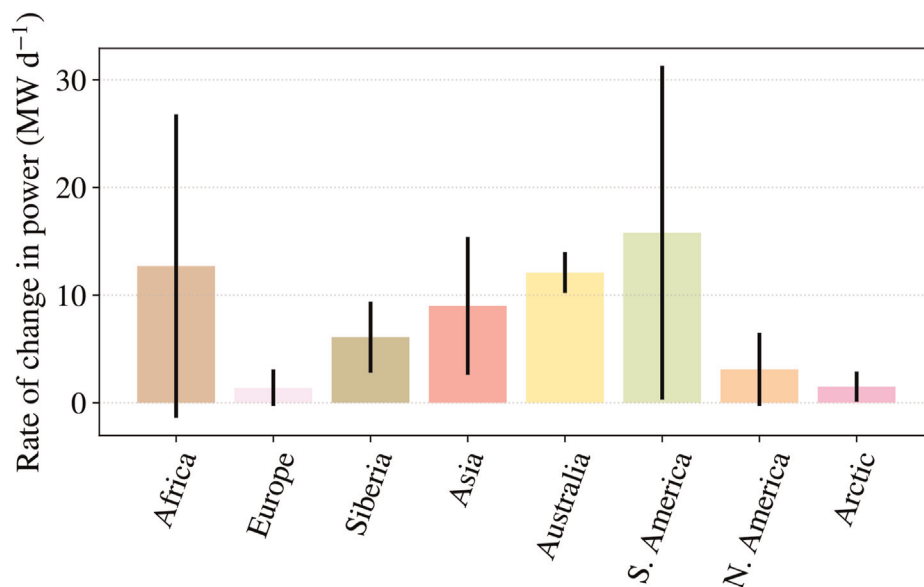


Fig. 6. The rate of change of daily power, between 1979 and 2013, from measurement of the gradient of a least squares polynomial fit of daily values of power.

approximation, serving to provide an indication of where the most promise may lie and a first iteration of an assessment of the global resource. Laws and Epps [24] claim that previous large-scale HEC resource assessments of tidal sites have included a significant degree of error. For example, one such assessment that used a tidal model, predicted flow velocities that differed from onsite measurements by $\geq 30\%$, leading to an error of a factor of two or more [71]. They state that previous global tidal potential estimates range from 100 TWh yr^{-1} to $17\,500 \text{ TWh yr}^{-1}$.

A previous riverine hydrokinetic resource assessment of the continental United States of America determined that there was a theoretical resource of 1381 TWh yr^{-1} [29]. The study used different methods for the 48 contiguous states and for Alaska, due to the availability of the National Hydrograph Dataset Plus (NHDPlus) for the contiguous states only, at this time. This study used the same standard hydrological equation for determining theoretical hydraulic power (Eq. (1)) as has been used in this current study. A

difference is that only river reaches with a mean discharge $Q > 28 \text{ m}^3\text{s}^{-1}$ (1000 cfs) were included in their assessment and river reaches containing dams or hydroelectric plants were excluded.

For comparison with this previous study, the method presented within this current paper was applied to a subset of data representing the contiguous states of the United States and Alaska, where only reaches with a mean discharge $Q > 28 \text{ m}^3\text{s}^{-1}$ were included (Table 1). This calculation does not include a removal of reaches containing dams or hydroelectric plants.

Jacobson et al [29]. state that validation of their hydrokinetic resource assessment was difficult, due to the lack of empirical data from existing HEC deployments. They further state that they know of no direct measurements of in-stream energy that could be used to validate their model and attribute this to both a lack of projects and also a reluctance to publish.

Miller et al. [30] carried out an earlier study to assess the technical riverine hydrokinetic resource of the United States.

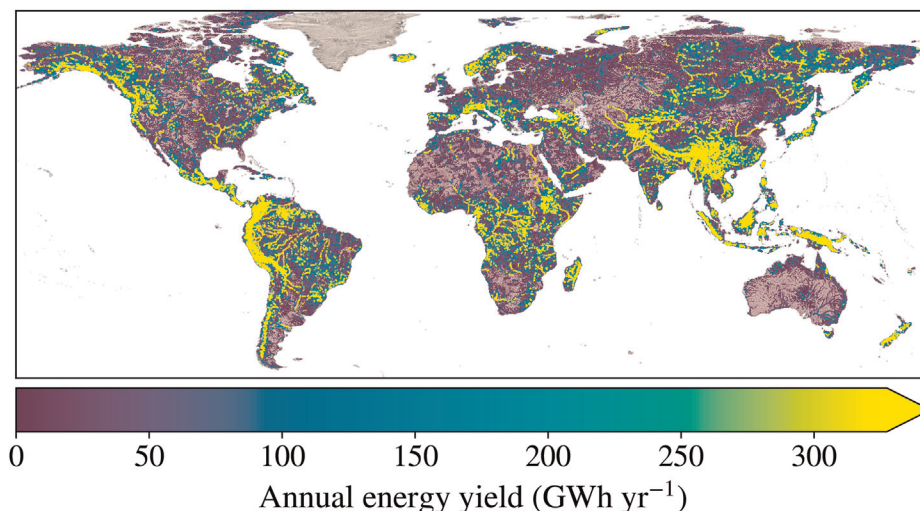


Fig. 7. Global distribution of theoretical riverine hydrokinetic resource.

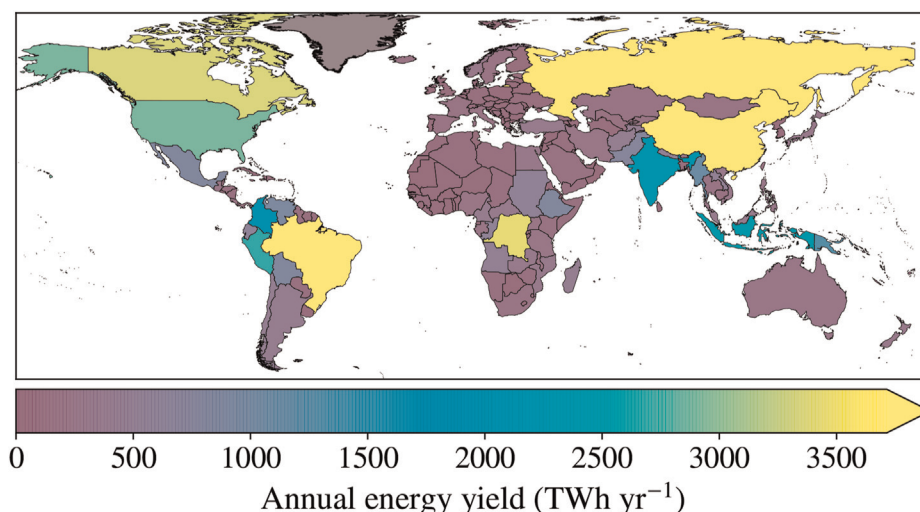


Fig. 8. Mean annual energy yield, by country, averaged over the period 1979–2013.

Accurately assessing a large-scale technical resource is challenging, requiring much more information and consideration of many more factors. Complications include determining the horizontal 2D distribution field for v and d ; and for the deployment of an array of turbines, the back-water effect caused by energy extraction. Their study determined the river reaches with the most potential, in 12 of 16 hydraulic regions, chosen using a criteria for including the region if mean discharge $Q > 113 \text{ m}^3\text{s}^{-1}$ (4000 cfs) and mean flow velocity $v > 1.3 \text{ ms}^{-1}$ (4.3 fps). An inconsistent criteria was used across these regions, but river reaches identified as having the greatest potential were assessed for recoverable power. An estimate was achieved by assuming turbine array deployment over 25% of the width and 25% of the length that met a minimum discharge criteria; with a turbine spacing of half a turbine diameter in each row and 5 turbine diameters spacing between the rows; where the turbine diameter is 80% of the mean depth; and the power coefficient $C_p = 40\%$. This method resulted in an aggregate mean annual power of 12 500 MW, yielding 110 TWh yr^{-1} . This result is a technical resource assessment, not a theoretical resource assessment, so comparison is difficult. Still, a coarse estimate of the technical resource can be determined by multiplying the theoretical resource

by a Significant Impact Factor (SIF), which is intended to represent the percentage that can be extracted without significant economic, or environmental effect. It should be noted that this is a very rough, first-order estimate with high uncertainties, but still offers some means of comparison. Though this would be site specific, previous studies have used 20%, with the assumption that this would yield an upper limit [72]. This current study determined that the United States has a theoretical resource of $\sim 2900 \text{ TWh yr}^{-1}$, without filtering out any reaches according to a criterion for Q . Applying an SIF of 20% provides an estimate of the technical resource to be 580 TWh yr^{-1} . An SIF of 4% corresponds with an estimate of the technical resource of the United States being 110 TWh yr^{-1} , as calculated by Miller et al. [30], if assuming the theoretical resource to be 2900 TWh yr^{-1} .

UMA Group [73] carried out a study in Canada, but only assessed the hydrokinetic potential of certain rivers that met the minimum criteria of $Q > 450 \text{ m}^3\text{s}^{-1}$, $v > 1.5 \text{ ms}^{-1}$, $w > 50 \text{ m}$ and $d > 3 \text{ m}$. This study included assumptions of uniformity along very long reaches (100s of kilometers) and used the Manning formula (Eq. (6)). Data was obtained from topographic maps and HYDAT, an archival database of daily and monthly means of flow, water levels and

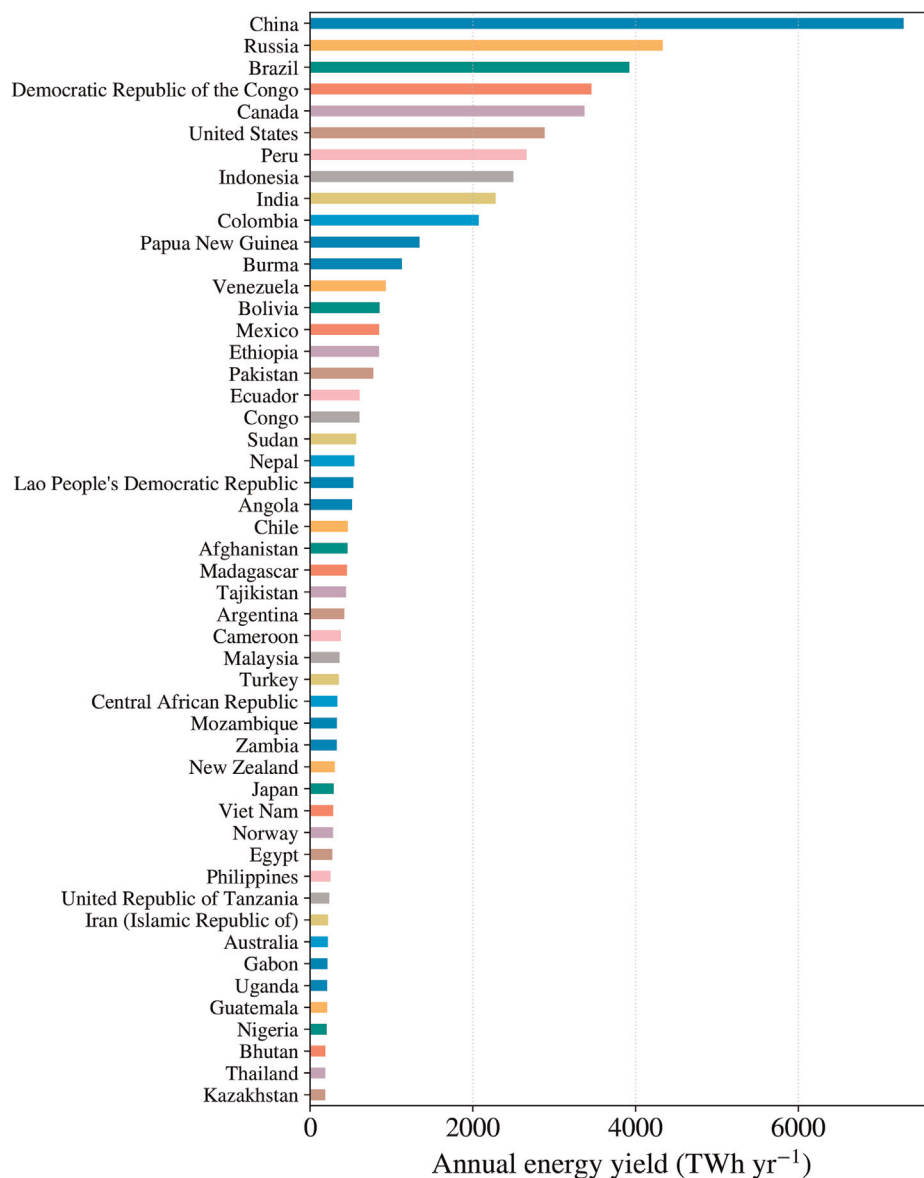


Fig. 9. Mean annual energy yield of the top 50 countries.

sediment concentrations across Canada [74]. Validation with the results of these studies is challenging, due to the criteria used.

Close proximity of communities to rivers and streams is common, with over 50% of the world's population living less than 3 km from a surface freshwater body and only 10% living more than 10 km away [75]. A correlation has been identified between population, need for electrification, poverty and river distribution [20]. This correlation is more dominant in Asia, Central Africa and South America, which are regions we have shown evidence to suggest offer promising potential for HEC.

HEC technology has been described as being 15–20 years behind the technology of wind power generation [76]. Hopefully this study goes some way to supporting this developing technology, addressing resource assessment: one of the main identified challenges it faces.

Jacobson et al. [29] assessed the hydrokinetic resource of the contiguous United States, using a method similar to that outlined here. The results of their study are comparable to those we present

for the same region (Table 1). Both their study and ours use the standard hydrological equation for determining theoretical hydraulic power (Eq. (1)). The derivation of this equation is from gravitational potential energy (see Section 2.1). For this reason, it could be argued that Eq. (1) is most applicable to a consideration of a resource assessment from a hydrostatic perspective, rather than a hydrokinetic perspective. Future research might look to develop a method that focuses on flow velocity, to reflect a technology (HEC) that uses the energy of flowing water directly, rather than possibly focusing on a technology (conventional hydropower) that uses the impoundment of a hydraulic head. This may prove difficult, since the determination of flow velocity, by remote sensing or hydrological modelling, is more challenging than for discharge and in the field of large-scale river hydrology there is a focus on quantifying the volume of water in rivers and streams [42]. Previous efforts have used the Manning formula (Eq. (6)), but have encountered a sensitivity to river roughness that necessitates local determination of the Manning roughness coefficient n [77].

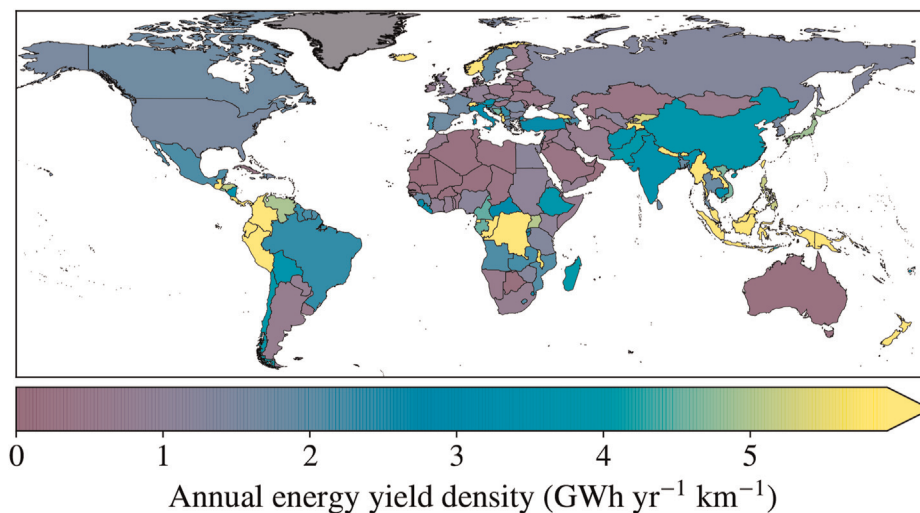


Fig. 10. Mean annual energy yield relative to total river length, by country, averaged over the period 1979–2013.

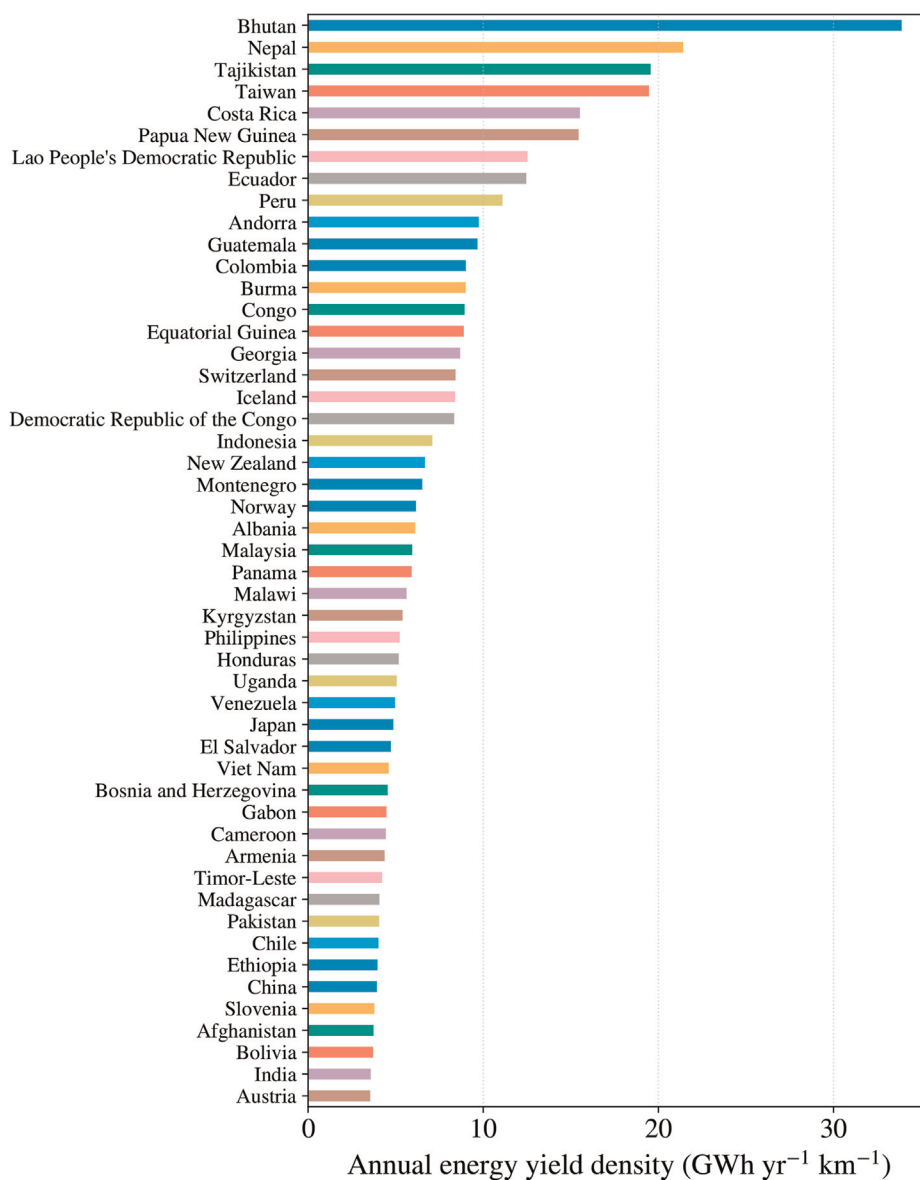


Fig. 11. Mean annual energy yield relative to total river length of the top 50 countries.

Table 1

Comparison of the results in this current study, for the continental states of America, to a previous resource assessment by Jacobson et al. [29].

	Estimated resource from Jacobson et al [29]. (TWh yr ⁻¹)	Estimated resource from this study with $Q > 28 \text{ m}^3\text{s}^{-1}$ (TWh yr ⁻¹)
Contiguous states	1146	1350
Alaska	235	348
Total	1381	1698

5. Conclusions

The theoretical global riverine resource is estimated to be $58400 \pm 109 \text{ TWh yr}^{-1}$ and found to be concentrated in major rivers of the world and regions with significant elevation change. Resource assessment on a global scale inevitably involves an acceptance of large uncertainty, due to the current limitations of remote sensing and hydrological modelling. The results presented here aim to provide a first-order approximation of the overall potential for hydrokinetic energy conversion, an understanding of temporal variations and an indication of the regions where this technology may be effective. Improvement upon this may result from developing a methodology that is focused upon the kinetic energy in rivers, instead of hydrostatic gravitational potential energy. Better quality data is also necessary, with the upcoming Surface Water Ocean Topography (SWOT) mission seeming the most promising source for this. Resource assessment has been identified as one of the main limitations in the development of hydrokinetic energy conversion technology. This study contributes towards addressing this challenge, establishes a sound method for hydrokinetic resource assessments and aids determination of where regional resource assessments should focus to reduce uncertainty.

CRediT authorship contribution statement

Michael Ridgill: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Simon P. Neill:** Writing – review & editing, Supervision, Project administration. **Matt J. Lewis:** Writing – review & editing, Supervision. **Peter E. Robins:** Writing – review & editing, Supervision. **Sopan D. Patil:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Thank you to the authors of Global Reach-level A priori Discharge Estimates (GRADES) for making their data available and for kindly responding to enquiries. Repetitive Energy Company (REC) have been kind enough to sponsor the post-graduate research of Michael Ridgill. We appreciate the funding support from Knowledge Economy Skills Scholarships (KESS 2). KESS 2 is a pan-Wales higher level skills initiative led by Bangor University on behalf of the HE sector in Wales. It is part funded by the Welsh Government's European Social Fund (ESF) convergence programme for West Wales and the Valleys. We acknowledge the support of the Supercomputing Wales project, which is part-funded by the European Regional Development Fund (ERDF) via Welsh Government. The authors acknowledge the support of SEEC (Smart Efficient Energy Centre) at Bangor University, part-funded by the European Regional Development Fund (ERDF), administered by the Welsh Government.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.renene.2021.04.109>.

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