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Updated Theoretical Resource Assessment for US Riverine Hydrokinetic Energy

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Abstract

We present a theoretical resource assessment of riverine hydrokinetic energy for the United States using the latest National Water Model version 3.0 (NWMv3.0) and the National Hydrography Dataset Plus version 2.1 (NHDPlusV2.1). These data sources enable a higher-resolution and more comprehensive assessment than the previous one by EPRI in 2012. Using NWMv3.0, which contains retrospective datasets with all hydrologic units (HUs) in the US, we cover all HUs in the contiguous United States (CONUS) and two HUs (Hawaii and Puerto Rico) outside the CONUS (oCONUS), providing a detailed spatiotemporal analysis of hydrokinetic energy resources. We observe a 25% increase in the total theoretical hydrokinetic energy potential compared to the previous study in 2012 by EPRI. We also quantify inter-annual and seasonal variability to present the temporal stability of hydrokinetic energy by analyzing hourly (15-minute for Hawaii) flowrate data. These results offer valuable insights for energy planners, project developers, and researchers, supporting more stable and efficient energy supply planning. In future research, we will address data limitations, particularly for Alaska, to further refine hydrokinetic energy potential estimates.

Keywords: Hydrokinetic Energy; Theoretical Resource Assessment; River Current; Annual Energy Production

1. Introduction

The river hydrokinetic industry, including energy planners, developers, and researchers, requires comprehensive information on the available hydrokinetic resources. This includes theoretical and technical resources, their geographical distribution, and seasonal variations. Efforts by the Department of Energy (DOE) to conduct marine and riverine hydrokinetic energy resource assessments have been ongoing. With recent improvements in hydrologic model hindcast data for the US, the most recent assessment of the US river hydrokinetic resources, conducted over a decade ago using the best available hydrologic model data, is now outdated. The Electric Power Research Institute (EPRI) has reported the overall theoretical hydrokinetic resource in CONUS and Alaska using National Hydrography Dataset Plus

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V1 (NHDPlusV1) data and some extra resources, estimating the theoretical resource to be approximately 1,300 TWh/yr [1]. However, EPRI used mean annual flowrate and bulk velocity, thus not enabling an assessment of the temporal variability of the resource [1].

This paper addresses and answers two primary research questions: 1) How much theoretical hydrokinetic resource is available, and how is it distributed in space and time? 2) What additional data and information is useful for the industry, including additional parameters and insights into seasonal and inter-annual variability? We present an in-depth analysis of the theoretical variability of riverine hydrokinetic energy resources across 18 Hydrologic Units (HUs) within the Contiguous United States (CONUS) and 2 HUs (Hawaii and Puerto Rico) outside the CONUS (oCONUS). We update and expand upon previous assessments by the EPRI in 2012 to enable a more comprehensive understanding of the spatiotemporal distribution and a more refined estimate of the magnitude of the CONUS theoretical resources and their uncertainty. We also provide high-fidelity information on the available US riverine hydrokinetic resources for industry stakeholders, including energy planners, industry project developers, and researchers.

2. Data and Methodology

2.1. Data

Recently, higher resolution and more accurate hydrologic models have been developed. Comparing hydrologic models, National Water Model v2.1 (NWMv2.1) has some advantages with its higher temporal resolution spanning a longer period and having retrospective data to a recent year [2]. Also, NWMv2.1 performs better on high-flow-focused metrics [3]. Therefore, we chose the most recent NOAA National Water Model v3.0 (NWMv3.0) Retrospective Dataset published in 2024, covering the US, including the CONUS, Alaska, Hawaii, and Puerto Rico.

NWMv3.0 has a 44-year interval (Feb 1979 through Jan 2023) of hourly retrospective simulation dataset for 2,776,734 flowline segments covering CONUS, a 39-year interval (Jan 1981 through Dec 2019) of hourly dataset for 391,528 flowline segments in Alaska, a 20-year interval (Jan 1994 through Dec 2013) of 15-min dataset for 13,637 flowline segments in Hawaii, and a 15.5-year interval (Jan 2008 through Jun 2023) of hourly dataset for 14,017 flowline segments in Puerto Rico. Note that the CONUS and oCONUS datasets have different periods of record (POR) and time steps. Employing a finer 10 m National Elevation Dataset (NED) in National Hydrography Dataset Plus V2.1 (NHDPlusV2.1), our approach marks a significant methodological advancement over the earlier assessment, which relied on mean annual flowrate and a 30-m NED in NHDPlusV1.

2.2. Methodology

Following the International Electrotechnical Commission (IEC) energy resource assessment standards (IEC TS 62600-301), the weighted average of flowrate in different time intervals (monthly, annual, and interval-wise) is calculated with a cumulative distribution frequency (CDF) histogram across 75 bins [4]. The weighted average flowrate is used to obtain each HU's monthly, annual, and interval-wise distribution of theoretical power and annual energy production (AEP). Interannual and seasonal variability is also presented to determine where the energy is spread more evenly throughout the year or concentrated within a specific period.

Using the flowrate data from NWMv3.0 and the slope and slope length data from NHDPlusV2.1, we calculated the theoretical power (P_{th}) with the following formula:

$$P_{th} = \gamma \cdot Q \cdot \Delta H \quad (1)$$

where γ is the specific weight of water, Q is the flowrate, and ΔH is the elevation difference. To determine a representative flowrate for each segment, we created a histogram with 75 bins based on hourly flowrate data (a 15-minute time step for Hawaii) per the IEC standard. The weighted average from this histogram was used as the representative flowrate. AEP was then calculated by multiplying the theoretical power by the total hours in a year (8760 hrs/yr).

This approach allows for a more statistically significant representation of flowrate values compared to previous studies, which relied on mean annual flowrate and did not account for the distribution characteristics of flowrate curves. Our methodology enables the estimation of inter-annual and seasonal variability in theoretical power, calculated using the following equations [5, 6].

$$t_i = \frac{\sigma[AEP(Y)-(S_1Y+S_2)]}{E(AEP)} \times 100\% \tag{2}$$

$$t_m = \frac{\left[P_{th}(M)\cdot\frac{T_{43year}}{T_{month}}\right]_{max} - \left[P_{th}(M)\cdot\frac{T_{43year}}{T_{month}}\right]_{min}}{sum\ (P_{th}(M))} \tag{3}$$

Inter-annual variability, t_i, is defined as a normalized standard deviation of the detrended AEP, which is the difference between the annual AEP, $AEP(Y)$, and the linear regression line, $S_1Y + S_2$. Seasonal variability, t_m, is calculated as the difference between the maximum and minimum period-weighted monthly theoretical power, normalized with the sum of monthly theoretical power.

3. Result and Discussion

3.1. Interval

We defined an interval as the period within which complete monthly data from January to December was available. Using the weighted average flowrate for these intervals, we calculated the AEP. To compare theoretical AEP computation results with the previous study done by EPRI in 2012, we initially computed the AEP using only flowline segments with flowrates exceeding 1000 cfs. The result shown in Fig 1 has an AEP of 1291.45 TWh/yr for the US (excluding Alaska), which is 13% higher than the 1146.4 TWh/yr reported in previous studies. For flowline segments having mean flowrate over 1000 cfs, in our study, HU17 Pacific Northwest has the largest AEP, while HU09 Souris-Red-Rainy, including parts of Minnesota, North Dakota, and South Dakota, has the smallest.

Limiting segments above 1000 cfs reduces the dataset from approximately 2.9 million records to 70 thousand records, which is computationally efficient but not ideal for a comprehensive theoretical power assessment that includes small distributed (off-grid) hydrokinetic power generation opportunities. Theoretical power aims to quantify the total potential theoretical energy, requiring the inclusion of all flowline segments. Removing the 1000 cfs limit as a constraint, the AEP for the US (excluding Alaska) is shown in Fig 2 to be 3076.19 TWh/yr, significantly higher than the 2461.41 TWh/yr estimated using the simple arithmetic mean flowrate from NHDPlusV2.1—an increase of approximately 25%. About 2.68 times greater theoretical AEP is spread throughout the United States compared to the previous study by EPRI [1].

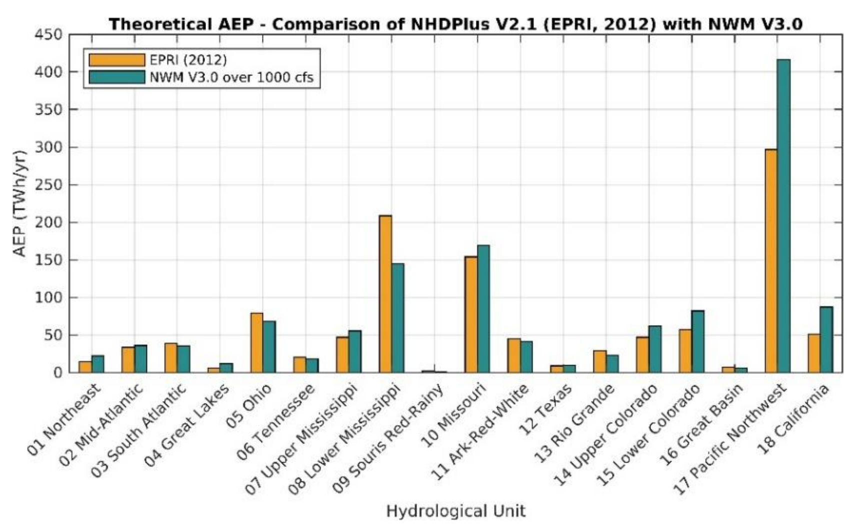

Fig. 1. Comparison of theoretical AEP calculated using NWMv3.0 retrospective dataset and that in EPRI's report [1], with flowline segments over 1000 cfs

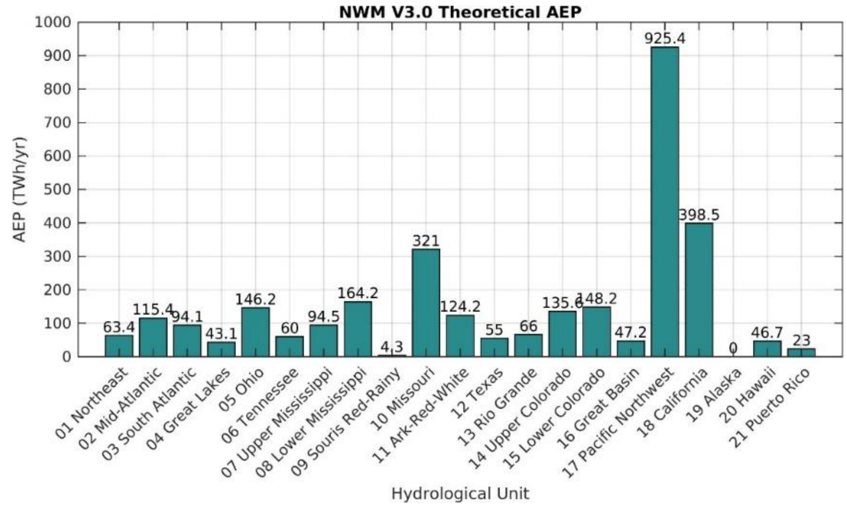

Fig. 2. Theoretical AEP calculated without flowrate limitation.

3.2. Temporal Variability

Based on the calculations of annual and monthly theoretical power, we also assess the temporal variability of riverine hydrokinetic energy. The fluctuation in theoretical power over time can be used to assess whether the energy is concentrated during specific periods or if riverine hydrokinetic energy can provide a stable energy supply. Due to the different data collection periods for the CONUS and oCONUS regions, temporal variability is calculated only for the CONUS region.

First, inter-annual variability is calculated using Eq. (3) and shown in Fig 3(a). The Hydrologic Unit (HU) with the highest variability was HU12 Texas at 51.68%, while the HU with the lowest variability was HU04 Great Lakes at 12.59%. Interestingly, the inter-annual variability for the entire CONUS region is 5.25%, which is lower than the variability of individual regions. This suggests that, although there may be some inter-annual variability in each HU due to factors such as differences in annual precipitation rates, the overall energy supply for the CONUS region does not vary significantly from year to year.

The seasonal variability shown in Fig 3(b) is assessed using the seasonal variability index, Eq. (4), which is the normalized difference between the month with the highest theoretical power and the month with the lowest power. The HU with the highest seasonal variability was HU14 Upper Colorado, with an index value of 2.03, while the HU with the lowest variability was HU15 Lower Colorado at 0.54. The Seasonal variability index for the CONUS region was calculated to be 1.03. The index is heavily influenced by changes in monthly theoretical power, with interesting behavior in that the eastern United States generally shows maximum power in the spring and the western United States in the summer.

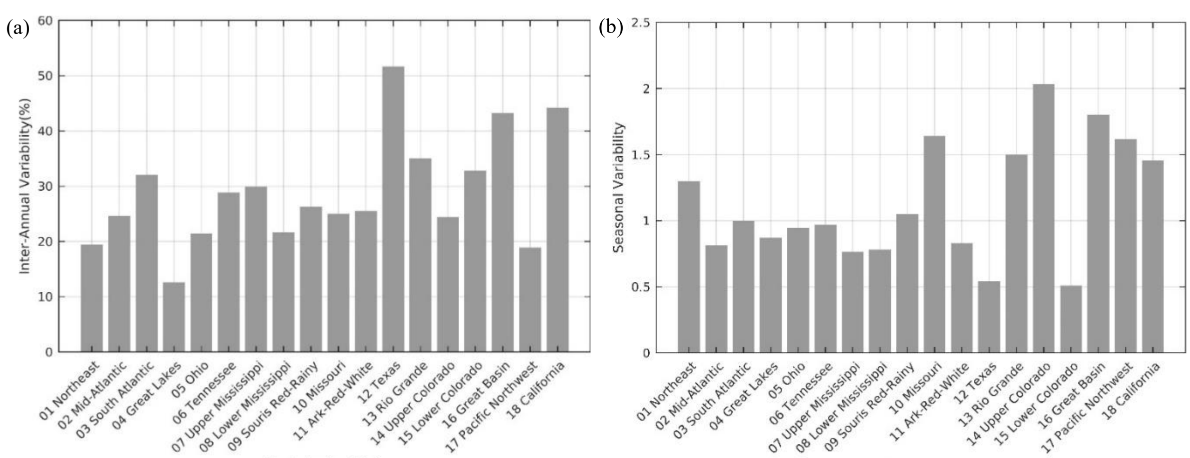

Fig. 3. (a) Inter-annual variability (b) Seasonal variability index of each Hydrologic Unit

4. Conclusion

By utilizing the latest NWMv3.0 flowrate data, we present updated estimates of theoretical power, including the magnitude of the US theoretical hydrokinetic resource and how it is distributed spatially and temporally. We also introduce seasonal and inter-annual variability indices as summary metrics.

This improved resource assessment is enabled by a longer dataset, hourly flowrate, and higher-resolution elevation dataset and including all flowline segments, without a flowrate over 1000 cfs limitation. The use of hourly flowrate data (15-minute intervals for Hawaii) enables a detailed temporal variability, which was not feasible in the previous study. Importantly, we calculate the total theoretical power potential of all US rivers, offering a more comprehensive assessment of hydrokinetic energy.

This study provides several key insights into the theoretical hydrokinetic energy resources of US rivers. Our analysis quantifies inter-annual and seasonal variability for each HU, providing fundamental data for energy planning and development. The findings indicate that while individual HUs may exhibit significant inter-annual variability, the overall variability across the US is minimal. This suggests that hydrokinetic energy supplies in some regions can compensate for lower supplies in others, ensuring more stable energy availability. Moreover, despite ongoing climate change, the anticipated decrease in AEP is not as significant as expected, highlighting the robustness of hydrokinetic resources.

Despite the advancements made in this study, there are still areas that require further investigation. One significant limitation is the absence of slope and slope length data for Alaska in the NHDPlusV2.1 dataset, which currently prevents the calculation of elevation difference (ΔH) for Alaska. We will focus on utilizing elevation data from NWMv3.0 to compute these elevation differences and accurately estimate Alaska's theoretical hydrokinetic energy. Accurate calculation of Alaska's theoretical hydrokinetic power is essential for a complete understanding of hydrokinetic energy resources in the US and will provide valuable insights for energy planners and project developers.

It should be underscored that hydrokinetic energy resource assessments' enhanced accuracy and reliability can be achieved through updated methodologies and datasets, offering valuable insights for developing and optimizing sustainable energy solutions. Energy planners and project developers can use this thorough analysis for reconnaissance and feasibility studies to assist with initial project scoping and planning.

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