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Hydrokinetic energy conversion: Technology, research, and outlook

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ABSTRACT

Interest in the advancement of *hydrokinetic energy conversion* (HEC) technology has grown substantially in recent years. The hydrokinetic industry has advanced beyond the initial testing phase and will soon install demonstration projects with arrays of full-scale devices. By reviewing the current state of the industry and the cutting edge research this paper identifies the key advancements required for HEC technology to become commercially successful at the utility scale. The primary hurdles are: (i) reducing the cost of energy, (ii) optimizing individual turbines to work in concert considering array and bathymetry effects, (iii) balancing energy extraction with environmental impact, and (iv) addressing socio-economic concerns.

This review is split into three primary sections. The first section provides an overview of the HEC technology systems that are most likely to be installed in commercial arrays. The second section is an in-depth literature review. The literature review is sub-divided into five areas that are positioned to significantly impact the viability of HEC technology: (i) site assessment, (ii) turbine design, (iii) turbine wake modeling, (iv) array performance, and (v) environmental impact. The final section presents an outlook for the HEC industry and future research.

Contents

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1. Introduction

With the growing recognition of global warming, more governments, research centers, and corporations are committing resources to the advancement of renewable energy technologies. There is not one renewable energy resource that will be a panacea for the world's energy needs. In order to transition from fossil fuel based energy resources, humankind must tap into a variety of renewable resources. As each country evaluates its resources, many have recognized hydrokinetic energy as a significant contributor to its renewable energy portfolio.

The purpose of this review is to summarize and synthesize the most crucial areas of research necessary to advance *hydrokinetic energy conversion* (HEC) technology towards widespread commercialization. In doing so, another aim of this review is to place a stake in the ground from which more advanced, cross-disciplinary work may be launched. HEC research encompasses a wide range of fields, including materials, fluid mechanics, and marine-biology (just to name a few). Furthermore, social and economic factors present significant hurdles to future HEC installations. This review touches on all of these areas and more.

The review begins with a summary of the most-advanced HEC technologies. It then takes the point-of-view of a design engineer by reviewing the cutting-edge research across all steps of project development. HEC research and development is a rapidly changing field and researchers are working to address numerous open questions. Questions range across all steps of project development: from site assessment, such as how to best characterize the resource at a site of interest; to device design, such as how to predict unsteady rotor loads and fatigue; to long-term operation, for example understanding the environmental impact of a large array of hydrokinetic turbines.

Finally, the review closes with an outlook for the HEC industry. A summary of the most advanced HEC projects across the globe is presented along with the non-technical hurdles that current HEC projects are facing. The review closes with a summary of the key hurdles identified and the steps that must be taken to address them.

2. Technology

Hydrokinetic energy converters can tap into three types of resources: *inland* (rivers), *tidal* (estuaries and channels), and *ocean* (currents). Most of the research and development of HEC technology to date has been directed towards tidal systems, and there has been relatively little development for inland or ocean current devices. Inland sites generally face more user conflicts than tidal or ocean sites. Ocean current device developers face a major hurdle in designing economical mooring systems for deep water sites [151].

Until recently, the HEC industry was dominated by small, entrepreneurial companies. In the last three years, however, a handful of large engineering and manufacturing firms have entered the field, primarily by buying designs near commercialization. The most active countries include the United Kingdom, Ireland, France, Spain, China, Japan, South Korea, Canada, and the United States [79]. Europe is at the forefront of technology development, with much of the activity in the UK due to its abundant wave and tidal resources. The European Marine Energy Center (Orkney, Scotland) provides plug-and-play testing sites and is currently developing international standards for the tidal and wave power industries [47].

In the following subsections, the most advanced designs in industry are presented. The subsections are defined by the three primary configurations of HEC systems: *axial-flow*, *cross-flow*, and *oscillating*. There are many designs that are in the conceptual and scale-model stages that are not mentioned in this review. Lago et al. [89] gives a comprehensive overview of the wide range of concepts for HEC systems. Here, the focus is on the systems that are closest to commercial-scale production.

2.1. Axial-flow systems

The vast majority of HEC systems are lift-based, axial-flow, tidal turbines. Drag-based systems do exist but they suffer from lower efficiencies compared to lift-based systems [6,73]. However, drag-based HEC systems can be useful in extracting energy from flows with exceptional amounts of debris, which is an important consideration for some sites [71].

Lift-based, axial-flow turbines use the same principles as aircraft wings, propellers, and wind turbines. The blades of a lift-based turbine are composed of two-dimensional hydrofoil cross-sections. Fig. 1 illustrates the velocities and forces (per unit radius) on a blade section: axial inflow velocity V_a and angular velocity ω. The effective freestream has magnitude $\sqrt{V_a+\omega r}$ and is oriented at pitch angle β to the rotor plane. The blade is pitched by angle θ such that a favorable angle of attack α is achieved, resulting in a lift force as shown. The lift and drag combine to produce torque $Q=(L \sin\beta - D\cos\beta)r$. The power extraction is then $Q\omega$. This shaft power is converted to electricity by a generator either directly coupled to the shaft (perhaps via a gearbox) or indirectly coupled via hydraulic transmission [18,122].

The lift force is the net resultant of the fluid pressure acting over the hydrofoil surface. Fig. 1 illustrates the pressure distribution for the exemplar case of a NACA 4418 hydrofoil at 4° angle of attack. Computations were performed using open-source code XFOIL [34], which employs a potential flow panel method coupled with an integral boundary layer solver. Because of the asymmetric (top-to-bottom) hydrofoil shape, water flows faster over the upper surface than the

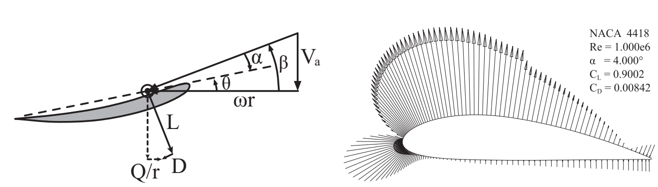

Fig. 1. (Left) Axial-flow turbine blade cross-section velocity and force triangles. (Right) Pressure distribution over a NACA 4418 hydrofoil at 4° angle of attack, computed using XFOIL [34].