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PERFORMANCE AND IMPACT OF HYDROKINETIC TURBINES IN RENEWABLE ENERGY SYSTEMS: A THEORETICAL APPROACH

Eugen-Vlad NĂSTASE

Abstract: *The growing demand for sustainable and reliable energy has increased interest in emerging renewable technologies. Hydrokinetic turbines offer a promising solution by converting the kinetic energy of flowing water without requiring large infrastructure. This paper presents a theoretical review of their performance and impact within modern energy systems. Fundamental principles of energy conversion, key performance parameters such as power coefficient and tip speed ratio, and common modeling approaches are analyzed. The integration of hydrokinetic systems into hybrid and decentralized networks is also examined, highlighting their potential to improve energy reliability. Despite advantages such as reduced environmental impact, challenges related to efficiency, scalability, and technological maturity remain.*

Key words: *hydrokinetic turbine, power coefficient, renewable energy, flow variability, hydraulic potential.*

1. INTRODUCTION

Global energy demand is projected to increase significantly in the coming decades due to population growth and economic development, while the depletion of fossil fuel resources and associated greenhouse gas emissions accelerate the transition toward low-carbon energy systems [1-4].

Although renewable sources such as solar, wind, and hydropower have advanced considerably, their large-scale integration remains constrained by intermittency, grid stability challenges and resource variability [5,6].

In this context, hydrokinetic energy has emerged as a promising solution, based on the direct conversion of the kinetic energy of flowing water into electricity without requiring large hydraulic infrastructure [7,8].

These systems can be deployed in rivers, tidal streams, and ocean currents, offering increased flexibility and reduced environmental impact. In addition, the significantly higher density of water compared to air enables greater energy extraction potential under comparable flow conditions [9].

Despite these advantages, the development of hydrokinetic turbines remains limited. Existing research is often focused on isolated aspects, such as turbine design, numerical modeling, or experimental investigations, resulting in a fragmented understanding of overall system behavior [7,10].

Furthermore, a coherent theoretical framework linking fluid dynamic principles, performance parameters, and system-level integration is still lacking [11].

Therefore, this work aims to provide a structured theoretical synthesis of hydrokinetic turbine performance and their role within renewable energy systems.

The paper aims to analyze energy conversion principles, evaluate performance parameters, review modeling approaches, and assess system integration.

The remainder of the paper is organized as follows: section 2 presents an overview of hydrokinetic energy systems, section 3 introduces the theoretical background and modeling approaches, section 4 analyzes turbine performance and influencing factors, section 5 discusses system integration aspects, while section 6 examines environmental and socio-economic impacts. Section 7 outlines current challenges and future research directions, and Section 8 concludes the paper.

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2. OVERVIEW OF HYDROKINETIC TURBINES

Hydropower is a mature and reliable renewable energy technology based on the conversion of hydraulic energy into mechanical and electrical power [13,15]. The total energy of a flowing fluid includes both potential and kinetic components, with conventional systems primarily exploiting the potential energy associated with hydraulic head. The available hydraulic power is expressed as:

$$P_h = \rho \cdot g \cdot Q \cdot H \quad (1)$$

where ρ is the fluid density, g is the gravitational acceleration , Q is the volumetric flow rate and head H is the hydraulic head [12]. The hydraulic power affected by the turbine efficiency is converted into mechanical energy (P_m) characterized by angular velocity (ω) and torque (M) as can be seen in figure 1.

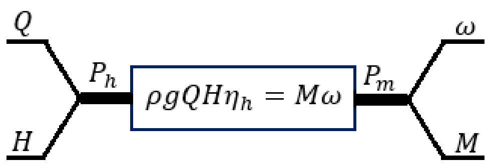

Fig. 1. Block diagram of energy transformations

Such systems typically require large-scale infrastructure, including dams and hydraulic devices to control and direct the flow of water for efficient energy extraction [13,14]. In contrast, when the hydraulic head is negligible, energy extraction relies on the kinetic component of the flow, where power depends on fluid velocity (v), is the swept area of the turbine rotor (A) and the fluid density:

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

Systems operating under these conditions are referred to as hydrokinetic turbines, as they extract energy directly from the velocity of water currents without requiring significant hydraulic structures [7,16,18]. Hydrokinetic turbines can be deployed in rivers, tidal streams, and ocean currents, offering increased flexibility and reduced environmental impact compared to conventional hydropower systems [18].

Due to the density of water being approximately 800 times greater than that of air, hydrokinetic systems provide significantly higher power density under comparable flow conditions [9,20].

From a design perspective, hydrokinetic turbines are classified into axial and vertical-axis (cross-flow) configurations [7,10,21]. Axial turbines generally achieve higher efficiency, whereas vertical-axis designs offer improved robustness under variable flow conditions.

A typical system consists of a turbine rotor coupled to a generator and supported by fixed or floating structures, integrated with control and power conditioning units [8,16].

To position hydrokinetic technologies within the broader renewable energy landscape, a comparative assessment with hydropower and wind energy systems is presented in Table 1.

Table 1

Comparative analysis of hydropower, hydrokinetic and wind energy systems

Parameter	Hydro classic	Hydro kinetic	Wind
Energy source	Potential+ kinetic	Kinetic (flow velocity)	Kinetic (air flow)
Power equation	$\rho g Q H$	$\frac{1}{2}\rho A v^3$	$\frac{1}{2}\rho A v^3$
Fluid density	~1000	~1000	~1.2 [6]
Energy density	Very high	High[5,6]	Low
Typical efficiency	Up to 90% [1]	(30-50)% [5]	(25-45)% [6]
Capacity factor	(40-90)% [2]	Moderate [5]	25-45% [6]
Infra structure	Dams required [3]	Minimal [5]	Towers
Environmental impact	High [3]	Low-moderate [7]	Low-moderate [6]
Predictability	High	Medium-high [5]	Low[6]
Scalability	Centralized	Modular	High
Technology maturiry	Very high	Emerging [5]	High [6]

As shown in Table 1, hydrokinetic systems represent an intermediate solution between conventional hydropower and wind energy, combining high energy density with reduced infrastructure requirements and lower environmental impact.

3. THEORETICAL BACKGROUND AND MODELING APPROACHES

The performance of hydrokinetic turbines is governed by the conversion of kinetic energy from flowing water into mechanical and subsequently electrical power. As introduced in Section 2 (Eq. 2), the kinetic power available in the flow scales with the cube of the velocity, which makes flow characterization a critical factor in energy extraction [12,16]. The extracted power is commonly expressed using the power coefficient C_P, defined as the ratio between extracted and available kinetic power:

$$P = \frac{1}{2} \cdot C_P \cdot \rho \cdot A \cdot v^3 \tag{3}$$

The coefficient C_P characterizes rotor level energy extraction and is fundamentally limited by fluid dynamics. Complete energy extraction would require the downstream velocity to approach zero, which is physically impossible, as the fluid must continue to move past the turbine. This constraint is described by actuator disk theory, leading to the Betz limit:

$$C_P^{max} = 0.0593 \tag{4}$$

In practice, the achievable values of C_P are significantly lower due to non-ideal flow conditions, including turbulence, wake rotation, viscous effects, and blade-induced losses [14,17,21].

A key dimensionless parameter governing turbine operation is the tip speed ratio (TSR):

$$TSR = \frac{\omega \cdot R}{v} \tag{5}$$

which defines the ratio between blade tip velocity and flow velocity. Turbine efficiency depends strongly on TSR, with each design exhibiting an optimal value corresponding to maximum C_P. At low TSR insufficient interaction limits energy extraction, while at high TSR, increased drag and flow separation reduce performance [7,21,22].

The $C_P - TSR$ characteristic provides a fundamental description of turbine behavior and is influenced by blade geometry, number of blades, and flow conditions.

Axial-flow turbines generally achieve higher peak efficiencies due to more favorable alignment with the flow, whereas vertical-axis turbines offer broader operational ranges under variable flow conditions, albeit at lower peak performance [10,21,23].

From a modeling perspective, hydrokinetic turbine performance can be analyzed using complementary approaches. Computational Fluid Dynamics (CFD) enables detailed analysis of flow structures and wake interactions but is computationally intensive and sensitive to modeling assumptions [17,21].

Analytical and semi-empirical models provide faster evaluation by combining theoretical formulations with experimental data, making them suitable for parametric and system-level studies [18,19].

At the system level, it is essential to distinguish between rotor efficiency and overall system performance.

While C_P refers to hydrodynamic efficiency, the global performance of a hydrokinetic system also includes mechanical and electrical losses:

$$\eta_{global} = \eta_{hydro} \cdot \eta_{mech} \cdot \eta_{elec} \tag{6}$$

In real-world applications, additional factors such as cavitation and corrosion affect performance and durability. Cavitation, caused by local pressure drops below vapor pressure, leads to bubble collapse, erosion, and efficiency loss [12,17]. Corrosion, driven by environmental conditions, results in material degradation and reduced component lifespan [16,20]. These phenomena impose practical constraints on turbine design and highlight the need for advanced materials, protective coatings, and optimized operating strategies.

4. PERFORMANCE ANALYSIS OF HYDROKINETIC TURBINES

The performance of hydrokinetic turbines is primarily governed by flow velocity, due to the cubic dependence of extracted power on current speed, which makes site conditions critical for energy yield [11,16].

Turbine efficiency is characterized by the $C_P - TSR$ relationship, which reflects the interaction between rotor speed and incoming flow. Each turbine exhibits an optimal tip speed ratio at which the power coefficient reaches a maximum value. Below this point, insufficient momentum exchange limits energy extraction, while above it, increased drag and wake losses reduce performance [7,10,21].

Typical peak values of C_P range between 0.3 and 0.5, depending on design and operating conditions remaining below theoretical limits due to turbulence, viscous effects, and flow non-uniformity [7,10,26].

Performance is further influenced by turbine geometry. Axial-flow turbines achieve higher efficiency under uniform flow conditions, whereas vertical-axis configurations provide improved robustness in multidirectional or turbulent flows, at the expense of lower peak efficiency [10,27,29].

Environmental and operational factors, including cavitation, corrosion, and biofouling, contribute to performance degradation over time by modifying blade surface characteristics and increasing mechanical loading [12,20].

From a modeling perspective, CFD enables detailed flow analysis, while analytical and data-driven approaches are more suitable for system-level optimization and control applications [17,21,29].

Overall, hydrokinetic turbine performance results from the interaction between flow conditions, turbine design, and environmental effects, requiring integrated optimization for efficient and reliable operation.

5. INTEGRATION INTO RENEWABLE ENERGY SYSTEMS

Harnessing relatively stable water currents, hydrokinetic turbines complement wind and solar generation while supporting overall energy system diversification [5,9].

The modular architecture supports their use in decentralized systems, notably in microgrids and off-grid applications across riverine and coastal regions with limited access to the grid [7,11].

Although less variable than wind and solar resources, hydrokinetic systems still require power conditioning to ensure grid compatibility. Maximum Power Point Tracking (MPPT) is commonly employed to maintain optimal operation under changing flow conditions [18,25].

Energy storage is often required to mitigate residual fluctuations and ensure supply–demand balance, especially in standalone or weak-grid systems. In hybrid configurations, hydrokinetic generation improves overall reliability by partially compensating for intermittency in solar and wind sources [4,6,28].

Overall, hydrokinetic systems are most effective within hybrid and decentralized energy architectures, where they enhance system stability and reduce dependence on highly variable resources.

6. ENVIRONMENTAL AND SOCIO-ECONOMIC IMPACT

By eliminating the need for dams and major river alterations, hydrokinetic turbines reduce environmental impact while preserving natural flows and limiting land use [7,9].

However, local ecological effects may occur, including risks to aquatic fauna due to blade interaction, as well as modifications of flow patterns that can affect sediment transport and habitat conditions. Additional impacts include underwater noise and ecosystem disturbance, depending on installation density and site characteristics [10,12].

Hydrokinetic systems are well suited to decentralized energy access due to their low infrastructure requirements, while their modular design enables scalable deployment and reduces upfront investment compared to large hydropower projects [7,8,28].

Nevertheless, economic viability remains dependent on site conditions, maintenance costs, and technology maturity. Operational challenges such as biofouling, corrosion, and debris interaction can increase lifecycle costs and reduce long-term reliability [12,20].

Overall, hydrokinetic energy represents a low-impact renewable option, but large-scale deployment depends on improving durability, reduced maintenance demands, and validated long-term environmental performance.

7. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Hydrokinetic energy systems remain at a relatively early stage of technological maturity, with limited large-scale deployment and operational experience compared to wind and solar technologies [5,7].

Key challenges include accurate modeling of highly variable and turbulent flow conditions, which strongly affect performance prediction and structural loading. While CFD provides detailed insight, its computational cost limits large-scale optimization, motivating reduced-order and hybrid modeling approaches [17,21].

Material degradation remains another major constraint, as cavitation, corrosion, and biofouling reduce component lifespan and increase maintenance requirements highlighting the need for advanced materials and protective strategies [12,20,24].

Efficiency optimization also remains critical, with real-world performance often below theoretical limits due to flow non-uniformity and control constraints, requiring improvements in blade design, TSR control, and real-time optimization [7,21].

At the system level, scalability is constrained by site-specific conditions (flow velocity, depth, environmental regulations), while the lack of standardized testing and performance metrics limits comparability across studies [11,28]

Future research is expected to focus on integrated approaches combining advanced modeling, improved materials, and data-driven methods, with hybrid physical–machine learning models offering strong potential for real-time optimization and predictive maintenance.

8. CONCLUSION

This study prosented a concise theoretical review of hydrokinetic turbines within renewable energy systems, emphasizing their governing physical principles, performance charactersitics, and system-level integration.

The analysis showed that energy extraction is primarily driven by flow velocity and rotor–flow interaction, while being fundamentally constrained by hydrodynamic limitations.

Compared to conventional hydropower, hydrokinetic systems enable deployment without large infrastructure, offering increased flexibility and reduced environmental impact, particularly in decentralized and hybrid energy systems.

However, large-scale adoption remains limited by challenges related to flow modeling, material degradation, efficiency optimization, and lack of standardization. Recent advances in numerical modeling and data-driven approaches provide promising pathways for improving performance and reliability.

Overall, hydrokinetic turbines represent a developing yet viable component of the renewable energy mix, with future progress dependent on advances in design, durability, and system integration.

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Performanța și impactul turbinelor hidrokinetice în sistemele de energie regenerabilă: o abordare teoretică

Cererea tot mai mare de energie durabilă și fiabilă a sporit interesul pentru tehnologiile regenerabile emergente. Turbinele hidrocinetice oferă o soluție promițătoare prin convertirea energiei cinetice a apei curgătoare fără a necesita o infrastructură mare. Această lucrare prezintă o analiză teoretică a performanței și impactului lor în cadrul sistemelor energetice moderne. Sunt analizate principiile fundamentale ale conversiei energiei, parametrii cheie de performanță, cum ar fi coeficientul de putere și raportul vitezei de vârf și abordările comune de modelare. De asemenea, este examinată integrarea sistemelor hidrocinetice în rețele hibride și descentralizate, evidențiind potențialul lor de a îmbunătăți fiabilitatea energetică. În ciuda avantajelor precum impactul redus asupra mediului, rămân provocările legate de eficiență, scalabilitate și maturitate tehnologică.

Eugen-Vlad NĂSTASE, Lecturer, PhD,“Gheorghe Asachi” Technical University of Iași, Romania, Department of Fluid Mechanics,Fluid Machinery and Fluid Power Systems, e-mail: eugen-vlad.nastase@academic.tuiasi.ro