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Bio-Inspired Flapping-Foil Energy Harvesters: Current Trends and Future Directions

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Abstract: Flapping-foil energy harvesters offer a promising bio-inspired method for converting kinetic energy from wind, currents, and waves into usable power by mimicking the oscillatory motion of fish fins and bird wings. These systems rely on coupled pitching–heaving kinematics, unsteady vortex dynamics, and fluid–structure interaction to extract energy efficiently. This review synthesizes advances in flow physics, structural design, and power-take-off strategies, emphasizing leading-edge vortex formation, wake-foil interaction, reduced-frequency effects, and phase synchronization as key mechanisms governing energy capture. Developments in experiments, theoretical models, and computational fluid dynamics have enabled optimization of kinematics, passive and semi-passive control, structural flexibility, and non-sinusoidal motion profiles. Environmental factors such as turbulence, shear flow, free-surface effects, and wave interaction are evaluated to assess operational robustness. Recent innovations include tandem-foil configurations, adaptive deformation, hybrid piezo-electromagnetic systems, and machine-learning-assisted optimization. Remaining challenges include achieving stable performance under variable flow conditions, scaling for practical deployment, and integrating realistic power-take-off models. Future opportunities lie in morphing structures, intelligent control strategies, and large-scale experimental and field validation to advance flapping-foil systems toward reliable renewable-energy applications.

Keywords: Flapping foil; Energy harvesting; Unsteady aerodynamics; Fluid–structure interaction; Vortex dynamics.

1. Introduction

The demand for clean and sustainable energy has accelerated the exploration of novel technologies capable of harvesting energy from natural fluid environments [1,2] . Bio-inspired flapping-foil energy harvesters have emerged as a promising alternative to conventional turbines by converting kinetic energy from wind, waves, and currents into usable power through oscillatory motion [3,4]. Inspired by fish fins and bird wings, these systems employ coupled pitching and heaving motions to interact with unsteady flow structures and extract energy via lift-induced forces [5–7]. Unlike rotary systems, flapping foils can operate efficiently at low flow speeds, exhibit reduced ecological disturbance, and offer potential for decentralized small-scale power generation in marine and aerial environments [8–11].

Attribute	Advantage	Caveat / design implication
Low-speed operation	High efficiency at low Reynolds numbers; viable in slow currents	Performance sensitive to phase tuning and k; site-specific optimization needed

Ecological footprint	No fast-spinning rotor; potentially lower risk to fauna	Oscillatory motions can disturb habitats if poorly sited; must assess local ecology
Deployment & footprint	Compact hardware; decentralized, small-scale installations possible	Foundation/mooring and alignment increase installation complexity in currents/waves
Control & phase tuning	Heave–pitch coordination enables LEV-assisted energy capture	Requires robust sensing/control to keep φ, f, and amplitudes in optimal ranges
Structural loads & fatigue	Lower tip-speed effects than turbines	Cyclic loads lead to fatigue; hinges/actuators and flexures need durability testing
Site-specific flow (shear, TI, free surface)	Can exploit shear layers and wake interactions for gains	Desynchronization in shear/turbulence reduces Cpy and Cpt; careful siting/modeling
PTO integration	Multiple PTO options (electromagnetic, hydraulic) allow tailoring	Added damping/gearbox losses can erase gains if not co-optimized with kinematics
Scaling & array effects	Tandem/array layouts can enable constructive wake capture	Near-field interference and spacing must be optimized to avoid performance loss
Environmental interactions	Potentially quieter and safer for fish and aquatic vegetation	Still requires EIA/permits; interactions depend on frequency, stroke, and location

The working principle of flapping-foil harvesters relies on unsteady aerodynamics, particularly periodic vortex formation, wake capture, and leading-edge vortex (LEV)-driven lift enhancement [12–15] . Through careful tuning of reduced frequency, oscillation amplitudes, and phase differences, these systems can reach favorable synchronization between fluid forces and foil motion, leading to high energy extraction efficiency [16,17] . Research efforts have expanded across experimental, computational, and theoretical domains, enabling improved understanding of vortex-foil interactions, structural dynamics, and power conversion mechanisms [18,19]. Recent advances include non-sinusoidal kinematics [20,21], active and passive actuation strategies [22–24], and adaptive deformation [4,25] to enhance energy capture across varying flow conditions.

Despite notable progress, challenges remain in translating laboratory-scale achievements to full-scale deployment. The performance of flapping foils is highly sensitive to environmental conditions such as turbulence [26], shear flows [27,28], and free-surface effects [29], which influence vortex behavior and induce power fluctuations. Moreover, realistic power-take-off (PTO) modeling, fatigue considerations, and long-term structural integrity are critical for practical implementation [30] . With emerging developments in machine learning-based flow control, flexible and morphing foils, and hybrid piezo-electromagnetic energy conversion systems, opportunities exist to further improve efficiency, adaptability, and scalability [31].

This review provides a comprehensive assessment of recent advances in flapping-foil energy harvesting, covering flow physics, kinematic and structural optimization, control strategies, array interactions, and environmental effects. Existing limitations and research gaps are highlighted to guide future developments toward reliable and efficient flapping-foil energy systems for renewable energy applications.

2. Fundamentals of Flapping-Foil Energy Harvesting

Flapping-foil energy harvesters convert kinetic energy from fluid flows into mechanical or electrical power by executing combined pitching and plunging motions, inspired by the locomotion of fish fins and bird wings. Unlike conventional turbines that rely on steady aerodynamic principles, flapping foils exploit unsteady lift generation, vortex formation, and fluid–structure interaction to extract energy from oscillatory hydrodynamic forces [32–34] . The fundamental energy conversion mechanism is governed by the synchronized interaction between foil kinematics, fluid forcing, and vortex dynamics, where appropriate phasing between lift forces and motion yields positive network [13,35].

As illustrated in Fig. 1, the foil undergoes harmonic heaving $h(t)$ and pitching $\theta(t)$ about a pivot point, characterized by a mean pitch angle θ_0, stroke amplitude H_0, chord length c, and stroke distance d. Proper tuning of the heave–pitch amplitude, frequency, and phase offset is essential to ensure that peak aerodynamic forces align with foil motion, enabling efficient energy extraction through constructive vortex–foil interaction.

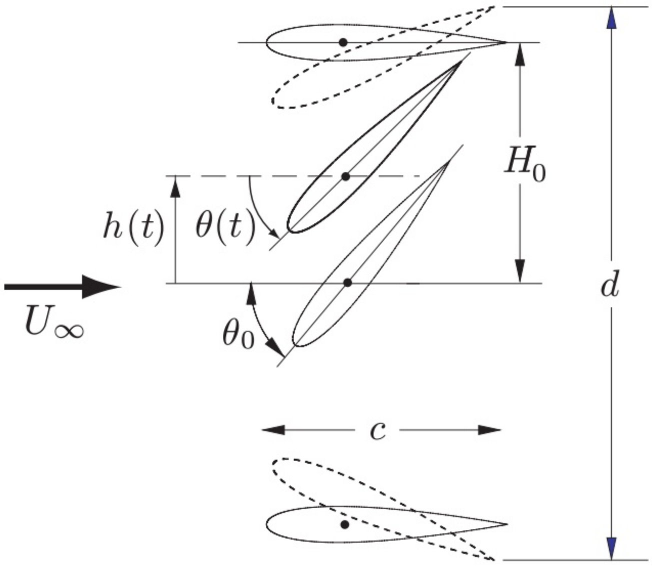


Fig. 1. Imposed pitching and heaving motion on flapping foil [17].

Table 1 summarizes the classification of flapping-foil energy harvesters based on their motion source and control strategy, ranging from purely passive devices driven by flow-induced instabilities to fully active systems with prescribed kinematics. Early studies established the feasibility of self-sustained oscillations under fluid forcing, demonstrating that passive systems can harness flow-induced instabilities for power extraction. Qadri et al. [36] experimentally investigated a two-degree-of-freedom plexiglass flat-plate foil and observed the onset of self-excited flapping beyond a critical flow velocity. Their results showed that inertial loading, pitching amplitude, and flow speed play crucial roles in initiating and sustaining energy-productive oscillations, highlighting the importance of inertial tuning to synchronize foil motion with hydrodynamic forces.

Control strategies in flapping-foil harvesters range from passive to fully active systems. Semi-active designs adjust structural parameters such as pivoting location, damping, and stiffness, allowing the foil to dynamically respond to flow forcing. Jamil and Javed used a spring-damper model and Theodorsen's unsteady aerodynamic theory to optimize these structural properties and demonstrated improved energy extraction through parametric tuning [37] . In contrast, fully active systems impose prescribed pitching-heaving motions, offering greater control over vortex timing, leading-edge vortex (LEV) attachment, and wake dynamics. Studies incorporating non-sinusoidal motion profiles have shown that tailored kinematics enhance LEV formation, improve instantaneous lift, and power output [38].

Table 1. Classification of Flapping-Foil Energy Harvesters

Category	Motion Source	Key Features	Advantages	Limitations
Passive	Flow-induced oscillation	VIV/self-excited	Simple, low-cost	Flow-sensitive
Semi-passive	Structural tuning + partial actuation	Adjustable stiffness/damping	Balanced control-efficiency	Requires sensors
Active	Fully prescribed	Full control	Highest efficiency	Power + control

	motion			required

Overall, the fundamentals of flapping-foil energy harvesting rely on three key elements: (i) effective coupling of foil motion with flow-induced forces, (ii) exploitation of unsteady aerodynamic mechanisms such as LEV formation and wake capture, and (iii) appropriate structural and control strategies to maintain energetic synchronization. These principles establish the foundation for further developments in kinematic optimization, flow-control techniques, and adaptive structural designs.

3. Fluid Dynamics and Mechanisms of Energy Extraction

Flapping-foil energy harvesters rely on unsteady fluid dynamics, where vortex formation, shedding, and wake interaction govern force generation and power extraction. Unlike steady aerodynamic devices, these systems harness transient flow structures—particularly the leading-edge vortex (LEV), trailing-edge vortex (TEV), and vortex-induced pressure gradients—to generate lift and convert it into usable power. The LEV forms on the suction side during the upstroke or downstroke and remains attached for a finite duration, strengthening suction and significantly amplifying instantaneous lift when properly synchronized with foil motion, as illustrated in Fig. 2. This transient vortex attachment enhances energy extraction, distinguishing flapping systems from conventional steady-state lifting bodies.

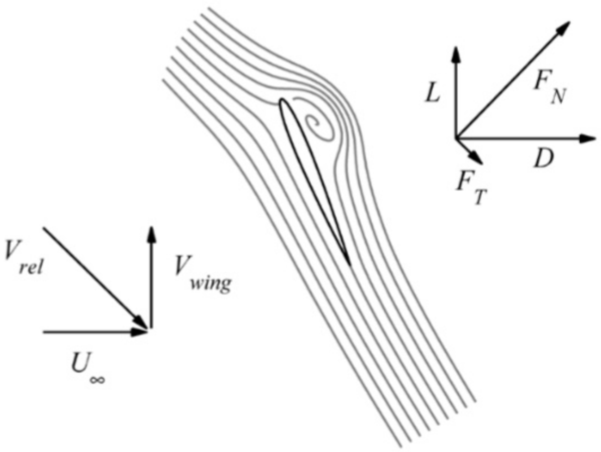


Fig. 2. Illustration of leading-edge vortex-driven power generation on a vertically oscillating foil in a horizontal freestream [8].

Flow-kinematic parameters, including reduced frequency, plunge and pitch amplitudes, and phase angle, strongly influence wake topology and flapping-foil performance. Optimal performance typically occurs in the high-reduced-frequency regime, where LEV attachment and timely shedding contribute to coherent wake structures. Wu et al. [11] highlighted that wake morphology transitions—from von-Kármán to reverse von-Kármán patterns—are directly linked to propulsive and harvesting efficiency, and sensitive to Reynolds number and oscillation amplitude. Kamrani-Fard and Liburdy [39] demonstrated numerically that LEV criteria and discrete vortex modeling improve prediction of optimal operating conditions.

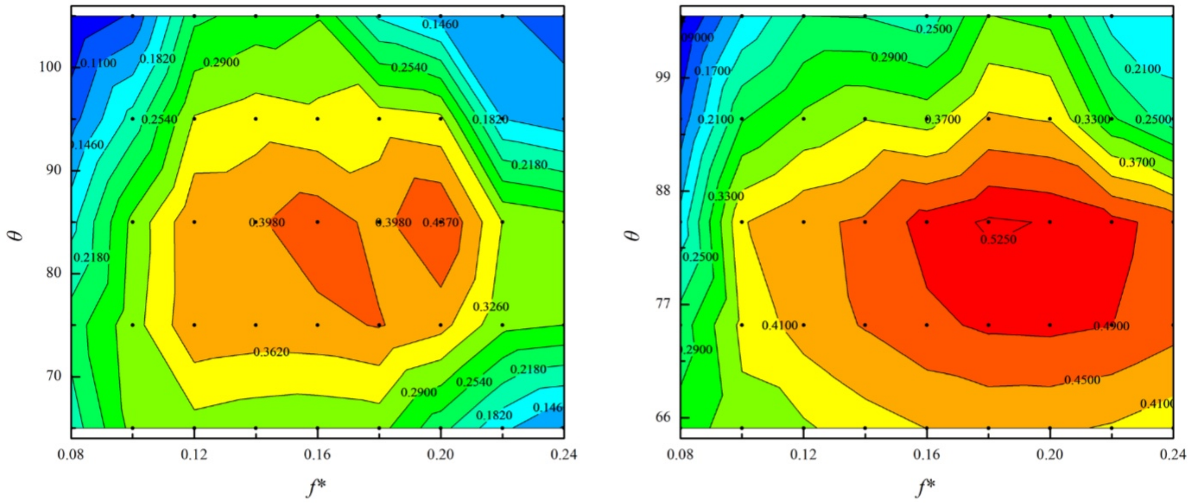
Surface features and geometry also affect vortex strength and flow separation. Abbas and Javed [40]reported that corrugated foils intensify LEV formation, improving power extraction over smooth profiles. Further, synthetic-jet actuation and circulation-control strategies have been shown to enhance momentum exchange at the foil surface. Shi and Sun [41] demonstrated that trailing-edge injection increases circulation and lift by over 22%[4], while Bai et al. [42] reported efficiency gains up to 76% using suction/blowing at higher Reynolds numbers[5].

Flow control strategies continue evolving, with studies showing that non-sinusoidal kinematics [43,44], spanwise flexibility [45,46] , and tuned structural damping improve vortex-foil synchronization. Recent CFD work has confirmed that turbulence [26], shear flows [27,28], and free-surface effects [29] disrupt LEV stability and reduce energy extraction, underscoring the importance of fluid-structure synchronization for real-world deployment.

4. Kinematic and Structural Optimization

The performance of flapping-foil energy harvesters strongly influenced by kinematic parameters — including heaving amplitude, pitching amplitude, reduced frequency, and phase angle — as well as structural properties such as stiffness, damping, and mass distribution. Optimal matching between foil motion and unsteady flow physics is essential to sustain leading-edge vortex (LEV) attachment, maximize lift, and enhance net power extraction. The phase relationship between pitching and heaving plays a particularly critical role; a phase lag near 90° typically promotes favorable LEV dynamics and wake capture, resulting in strong energy extraction efficiency [47].

Optimization studies have demonstrated that tuning oscillation amplitudes and motion trajectories produces substantial performance gains. Kinsey and Dumas showed that systematic variation of frequency and motion amplitudes can yield energy extraction efficiencies above 30% under ideal conditions [16] . Ashraf et al. [48] further reported that foil geometry (thickness and camber) and Reynolds number markedly influence harvesting efficiency [49]. Optimization methods such as response-surface modeling and genetic algorithms enable efficient exploration of design spaces, leading to enhanced kinematic tuning [50,51].



(a) (b)

Fig. 3. Contour maps of energy extraction efficiency versus reduced frequency and pitch amplitude for (a) non-deformable and (b) arc-deformable flapping foils, showing a broader and higher efficiency region for the deformable configuration. Taken from [52].

Structural flexibility plays a pivotal role in improving hydrodynamic response. Flexible foils can delay vortex shedding, enhance LEV stability, and passively adapt to flow variations. Zhu [46] demonstrated that spanwise flexibility improves thrust and harvesting efficiency compared to rigid foils. Su and Breuer [53] later showed that structural resonance between foil elasticity and unsteady forcing enhances energy extraction capability. Likewise, Wang et al. [54] found that structural damping influences oscillation amplitude and wake strength, implying a trade-off between stability and energy capture. Zhu et al. [52] further introduced an arc-deformable flapping wing, where synchronous chord-wise deformation actively modulates camber during each stroke. Their results showed that deformation amplitude and deformation-center position strongly influence efficiency, with optimal energy extraction achieved when the deformation center lies near the mid-chord and the deformation ratio β is moderate. As shown in Fig. 3, the deformable foil exhibits significantly higher efficiency over a wider range of reduced frequencies and pitch amplitudes than the rigid counterpart, highlighting the benefit of synchronized shape adaptation in expanding the high-performance operating envelope.

Semi-passive and passive configurations can exploit vortex-induced vibrations for self-sustained oscillations without external actuation. Michelin and Smith developed a theoretical model showing that appropriately tuned mass ratio and stiffness generate efficient vortex-induced motion [55]. The data-driven control strategies coupled with compliant structures can autonomously optimize motion trajectories and enhance energy harvesting [56].

Overall, effective energy extraction depends on coordinated optimization of foil kinematics and structural properties. Advances in passive flexibility, reduced-order modeling, and evolutionary algorithms continue to refine design strategies, while emerging techniques in machine-learning-based optimization provide a promising direction for real-time adaptive control in complex flow environments.

5. Configurations and Interaction Effects

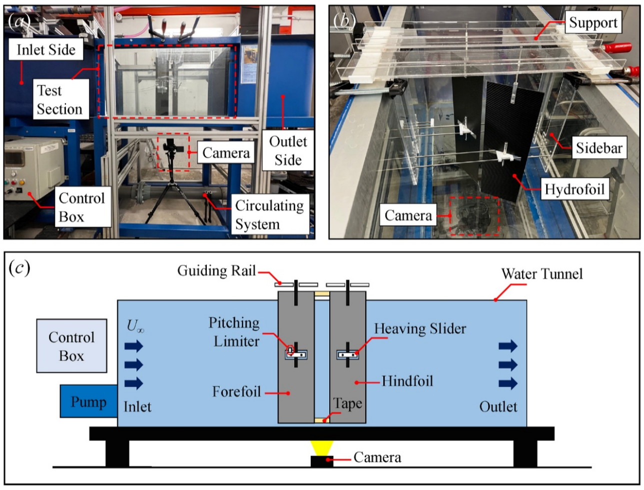


Fig. 4. Water-tunnel setup and tandem hydrofoil arrangement used to study wake-interaction effects. Adopted from [57].

The arrangement of multiple flapping foils and their interaction with surrounding flow structures significantly influence energy extraction performance. In multi-foil systems, wake-foil interactions can either enhance or reduce power output depending on spacing, phase synchronization, and inflow conditions [57,58]. Wang and Ng [57] demonstrated through experiments that reducing the spacing between the fore- and hindfoil strengthens wake coupling, allowing the downstream foil to benefit from the energized flow shed by the upstream foil. As shown in Fig. 5(a), both the forefoil and hindfoil efficiencies increase with pitch amplitude, with the smallest spacing (s = 0.03 m) yielding the highest gains due to stronger vortex-induced lift. This improvement carries over to the full array, where Fig. 5(b) shows the overall array efficiency steadily rising with pitch amplitude, again with closer spacing providing the greatest benefit. These results underscore that optimal spacing and pitch amplitude are critical to achieving constructive wake interaction and maximizing tidal-array performance.

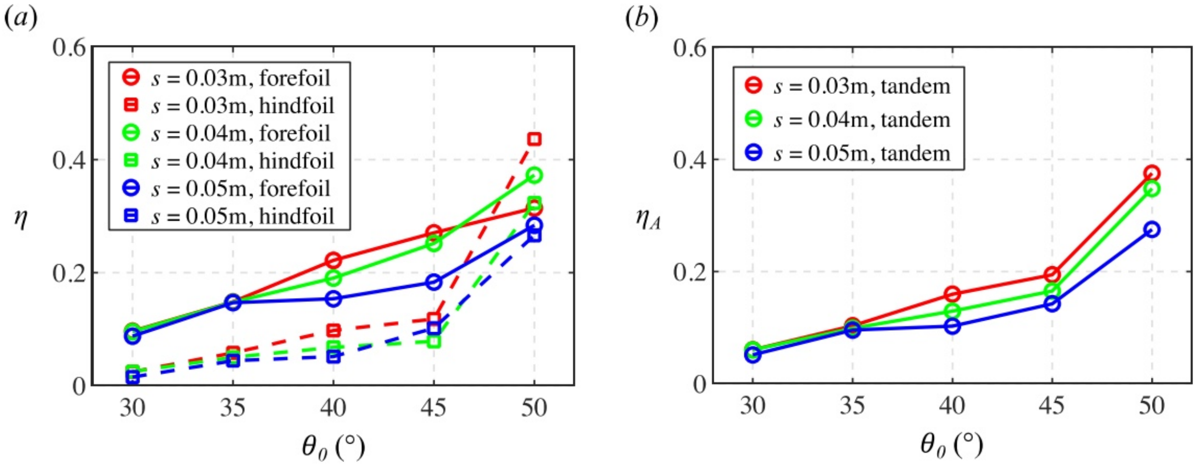


Fig. 5. Efficiency vs. forefoil pitch amplitude for different spacings:(a) forefoil and hindfoil efficiency; (b) total array efficiency, with closer spacing giving higher performance. Adopted from [57].

Optimal spacing and phase coordination play critical roles in harnessing beneficial wake effects. Kinsey and Dumas demonstrated that downstream foils could outperform single-foil systems under carefully tuned phase and separation distances [59]. Ma et al. [60] further showed that phase lag between foils strongly governs wake topology and can induce either thrust or drag augmentation. Xu et al. [61] reported that in tandem arrays, in-phase motion tends to maximize wake reinforcement, while anti-phase motion reduces energy transfer efficiency. Parallel and staggered foil configurations also exhibit distinct vortex interactions; staggered layouts have found to stabilize vortex shedding at moderate spacing, improving power performance [60,62].

Flapping foils operating in wakes generated by bluff bodies or upstream turbines show strong fluid-structure coupling effects. Downstream foils may lock into vortex shedding frequencies via wake-induced oscillations, enabling self-sustained motion for energy harvesting. Chatterjee et al. [63] demonstrated that operating a flexible foil in the wake of a cylinder enhances oscillation amplitude and energy extraction due to vortex forcing . Similarly, Dharmana et al. [64] found that wake-induced flapping improves hydrodynamic loading and harvesting potential in low-velocity currents.

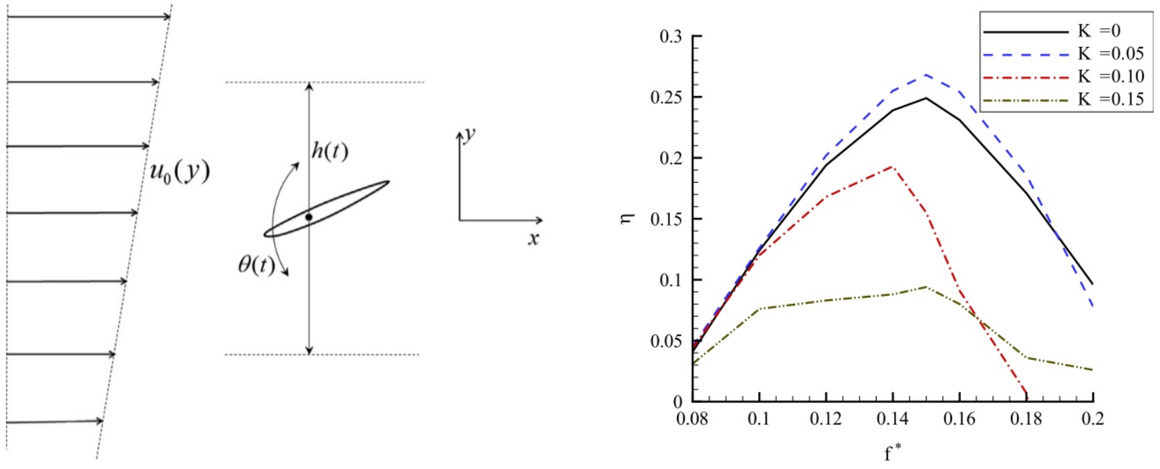
Environmental turbulence and flow unsteadiness significantly influence multi-foil configurations. Turbulent inflow disrupts LEV stability and alters pressure gradients across foils, potentially reducing power extraction. CFD studies by Delikan, and Bal [65] showed that unsteady inflow reduces downstream foil coherence, particularly at high turbulence intensities[8] . Meanwhile, Parekh and Jaiman [66] demonstrated that structured wake shedding from upstream bodies can synchronize foil motion, offering opportunities to harness ambient disturbance energy. Investigations into flapping arrays in wave-current conditions reveal that free-surface effects modify wake strength and dictate optimal vertical spacing and submergence depth [67].

Overall, inter-foil spacing, phase synchronization, and inflow structure are critical parameters governing energy extraction in multi-foil systems. Properly configured arrays can leverage constructive vortex interactions to enhance performance, while unfavorable configurations lead to significant efficiency loss. Continued research into 3D effects, turbulent wake dynamics, and adaptive phase control will be essential for scalable array-based flapping-foil energy systems.

6. Environmental and Practical Considerations

Realistic operating environments impose constraints that can markedly alter the hydrodynamics and net power of flapping-foil energy harvesters. Near the free surface, submergence depth and wave kinematics change pressure gradients, LEV stability, and effective added mass. Fully passive devices show a performance "window" at intermediate depths—typically a few chords below the surface—where wave–foil resonance augments heave response; outside this window, free-surface dissipation or ground-effect reduction of pressure recovery can diminish output. Regular waves close to the structure's natural frequency further amplify harvesting, underscoring the need to co-tune submergence and stiffness to site conditions [68].

Background shear—typical in rivers, estuaries, and tidal channels—alters vortex timing and pressure forces on flapping foils. Prior studies showed that shear can de-synchronize force–motion phasing, reducing power extraction, particularly in passive and semi-passive systems whose motion is governed by fluid forcing [69]. Cho and Zhu [70] further demonstrated that mild shear may slightly enhance efficiency by promoting favorable vortex phasing, but stronger shear disrupts leading-edge vortex synchronization, sharply reducing lift recovery and power, especially at higher reduced frequencies. As seen in Fig. 6(b), efficiency peaks at moderate frequencies in uniform and weak shear, then drops rapidly as shear intensifies.



(a) (b)

Fig. 6. (a) Schematic of a heaving–pitching foil operating in a linear shear profile, where the free-stream velocity increases with vertical position. (b) Energy-harvesting efficiency η versus reduced frequency f* for different shear rates. Mild shear slightly improves performance, whereas strong shear significantly reduces η and narrows the optimal frequency window due to disrupted vortex–motion synchronization (adapted from [70]).

Turbulence intensity and spectral content also matter. Moderate TI can energize shear layers and strengthen coherent LEVs, but high Turbulence intensity disrupts LEV attachment, increases cycle-to-cycle variability, and reduces mean power; semi-passive devices exhibit pronounced performance spread with increasing TI. These effects argue for controllers (or compliant structures) that adapt kinematics to stochastic inflow [71,72].

Geometric confinement and blockage—inevitable in channels, ducts, and farm layouts—modify effective inflow and vortex transport. Recent experiments and CFD quantify non-monotonic trends: moderate blockage can increase apparent velocity and lift, but excessive confinement leads to premature separation, altered wake modes, and degraded efficiency. Narrow-channel studies show that wall proximity and lateral spacing must be co-optimized with phase to avoid destructive interference in arrays [73–75].

Beyond hydrodynamics, practical issues determine delivered (not just hydrodynamic) power. Marine biofouling roughens surfaces, thickens boundary layers, and shifts optimal kinematics—causing measurable power loss over time and requiring maintenance or coatings. Flexible and hydro elastic elements improve robustness but introduce fatigue and durability concerns that must be assessed under site-specific load spectra. Accurate power-take-off (PTO) representations (electromagnetic or piezoelectric) are essential; ideal damping over-predicts output compared to coupled electromechanical models that include generator dynamics and structural feedback [76].

Taken together, environmental inflow (free surface, waves, shear, turbulence) and site constraints (blockage, fouling, durability, PTO) should be embedded in design and control loops. Submergence depth and natural frequency must be co-tuned; phase and reduced frequency should be adjusted for local shear/TI; and PTO parameters must be co-optimized with kinematics and flexibility to translate hydrodynamic gains into electrical power at scale [27,29,68,69,72].

7. Novel Designs and Hybrid Systems

Recent advances in flapping-foil energy harvesting have explored unconventional foil morphologies, bio-inspired structures, and hybrid transduction strategies to enhance performance and broaden application scope. Geometric tailoring—such as asymmetric profiles [77] , thick-leading-edge foils [78] , and trailing-edge modifications [79]—has been used to manipulate pressure gradients, delay separation, and strengthen leading-edge vortex (LEV) attachment for improved lift production. For instance, teardrop-like or blended bodies with slender trailing sections have been shown to yield higher efficiency compared to conventional NACA foils by promoting favorable vortex roll-up and stabilizing the wake . Deployable or adaptive trailing-edge flaps inspired by bird feathers have also demonstrated improved energy extraction by tuning vortex shedding timing in response to flow variations [22,31,78,80–82].

Flexible and morphing structures have emerged as promising configurations for self-adaptive energy harvesting. Chordwise-compliant foils enhance LEV stability and improve power coefficient at low Reynolds numbers, while spanwise-varying stiffness enables simultaneous control of bending and twisting, emulating fish fin biomechanics [4,25,63,83]. Shape-memory alloys, electro-active polymers, and anisotropic composite laminates have been integrated to realize tunable stiffness and flow-responsive deformation [84].

Hybrid systems integrating electromagnetic and piezoelectric transducers provide multi-modal energy conversion, making them suitable for low-power marine sensors and autonomous underwater vehicles. Magnetically levitated flapping harvesters minimize mechanical friction and enable broadband resonance, leading to higher power density at low excitation frequencies [85]. Piezoelectric sheets or patches embedded in flexible foils extract strain energy from hydro elastic deformation, producing supplemental power while also acting as passive dampers [86] . Fully coupled fluid-structure-electricity models demonstrate that piezoelectric power harvesting benefits from synchronized vortex loading and foil resonance [87].

Miniaturized devices and multi-degree-of-freedom hybrid actuators inspired by insect wings have also developed, enabling flapping-foil operation in micron-scale wind and water environments [88]. At larger scales, clustered hybrid units being investigated to simultaneously harvest vortex-induced vibrations and flapping-induced lift, especially for offshore moorings and tidal arrays [89]. Collectively, these developments highlight the expanding design space where geometry, smart materials, and multi-physics integration converge to enhance adaptability, efficiency, and robustness.

8. Challenges and Future Outlook

Despite rapid advancements in flapping-foil energy harvesting, several critical challenges remain before these systems can be deployed on a practical scale. The foremost barrier lies in translating laboratory-optimized conditions into real flow environments characterized by turbulence, shear layers, unsteady inflows, biofouling, and free-surface effects [28,29,90]. Such complexities disrupt leading-edge vortex (LEV) stability, alter force–motion synchronization, and reduce harvested power [91]. Furthermore, flapping-foil performance is sensitive to motion parameters and structural tuning; small deviations in phase lag, reduced frequency, or damping can significantly diminish efficiency [92,93]. Robust adaptive mechanisms and closed-loop controllers required to maintain optimal kinematics under fluctuating flow conditions.

Scaling and structural durability pose additional constraints. While flexible foils improve unsteady aerodynamic performance, they introduce fatigue, hydro elastic instabilities, and material degradation concerns over long-term deployment [91]. Coupling realistic power-take-off (PTO) models with fluid–structure interactions remain a key necessity, as hydrodynamic efficiency does not directly translate to electrical efficiency [94] . Fully coupled electromechanical modeling is required to avoid over-prediction of output. Field-scale evaluations of flapping-foil arrays are scarce, and wake interference patterns, blockage effects, and control of inter-foil phasing must be studied to realize scalable "foil farms" [95].

Emerging research directions focus on machine-learning-assisted optimization, surrogate modeling, and reinforcement-learning-based controllers capable of adjusting amplitude, frequency, and pitch-heave trajectories in real time [75,96]. Bio-inspired morphing foils, smart materials, distributed sensors, and compliant mechanisms offer promising strategies to expand operational bandwidth and resilience [97]. Ultimately, success will rely on interdisciplinary development combining fluid mechanics, structural dynamics, smart materials, control theory, and marine engineering. Continued efforts toward large-scale prototyping, long-duration offshore testing, and integrated PTO development will be essential to transition flapping-foil harvesters from laboratory prototypes to reliable renewable-energy solutions [98,99].

9. Conclusion

Flapping-foil energy harvesters continue to gain momentum as a promising bio-inspired pathway for extracting renewable energy from wind, current, and wave environments. Their ability to harness unsteady flow mechanisms such as vortex shedding, wake capture, and fluid–structure resonance offers unique advantages over conventional rotary systems, particularly in low-velocity and highly variable flows. Research efforts over the past decade have deepened understanding of unsteady vortex dynamics, optimized kinematic parameters, and explored structural flexibility and adaptive motion to enhance power extraction.

Significant progress has been made in developing passive, semi-active, and fully active configurations, expanding design strategies from rigid foils to flexible, morphing, and hybrid devices. Tandem and array arrangements have demonstrated potential for constructive vortex interaction, while modern control techniques and smart materials enabling self-adaptive and multi-modal harvesting. Environmental considerations such as turbulence, shear, and free-surface effects are increasingly integrated into design and simulation frameworks, improving realism and guiding deployment strategies.

Despite these advances, challenges remain in transitioning flapping-foil systems from laboratory-scale prototypes to robust field-scale energy solutions. Real-world flows impose dynamic and unpredictable conditions that can compromise vortex stability and power consistency. Practical limitations such as fatigue, durability, marine biofouling, and accurate power-take-off integration must be addressed to ensure long-term reliability and useful electrical output.

Future efforts should focus on real-time control, machine-learning-based optimization, high-fidelity fluid-structure-electric coupling, and long-duration deployment testing. Continued progress in materials, sensing, and adaptive control—combined with large-scale experimental validation—will be critical to realizing the full potential of flapping-foil harvesters as viable contributors to the renewable-energy landscape

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