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EDITORIAL

Editorial for Journal of Carbon Neutrality

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Abstract

Achieving carbon neutrality demands a fundamental transformation across energy, industry, technology, and policy sectors, supported by interdisciplinary scientific innovation. This paper presents a comprehensive overview of key technological pathways toward carbon neutrality, including energy decarbonization, resource efficiency, and nature-based solutions. It further highlights five emerging scientific frontiers, that is, photovoltaics with energy storage and electric mobility, chemical CO_2 valorisation, contrail mitigation, lightweight and low-carbon materials, and AI-driven healthcare decarbonization, to illustrate the breadth of research contributions essential for a net-zero future. Within this context, the authors focus on energy harvesting from fluid-structure interaction (FSI) as a representative cross-cutting technology. Recent advances in flow-induced rotation (FIR) of square cylinders and flexible flag dynamics are reviewed, with emphasis on the identification of multi-stable regimes, analytical modeling, and the development of a strongly coupled fluid-structure-piezoelectric interaction (FSPEI) framework. These findings underscore the potential of FSI-based systems to enable self-powered, low-carbon infrastructure and distributed energy solutions.

Keywords: carbon neutrality, fluid-structure interaction, energy harvesting, flow-induced rotation, flag flapping, Interdisciplinary carbon reduction technologies.

1 Introduction

Carbon neutrality refers to a state in which the total greenhouse gas emissions generated directly or indirectly by a country, region, or entity over a specific period are offset through carbon removal, storage, and other negative emission technologies, achieving a relative "zero emission" balance. Achieving this ambitious goal requires a fundamental transformation of socio-economic systems, guided by a comprehensive strategy that spans energy, industry, technology, policy, and international cooperation.

Key actions to realize carbon neutrality include:

- Controlling the total volume of fossil energy consumption while significantly improving energy utilization efficiency, implementing a renewable energy replacement action plan, and constructing a new power system centered on renewable energy sources.
- Promoting pollution and carbon reduction in

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key sectors: advancing green manufacturing in the industrial sector, enhancing energy efficiency standards in the building sector, and accelerating the adoption of green and low-carbon transportation.

- Achieving major breakthroughs in green and low-carbon technologies by accelerating research into frontier low-carbon technologies, promoting the application of pollution and carbon reduction technologies, and establishing a comprehensive technology evaluation and trading system along with innovation service platforms.
- Improving green and low-carbon policies and market systems, including refining the dual-target control system governing both total energy consumption and energy intensity, optimizing fiscal, pricing, financial, land, and government procurement policies to support green development, accelerating the development of carbon emission trading markets, and actively fostering green finance.
- Advocating green and low-carbon lifestyles by reducing waste and encouraging green mobility.
- Enhancing ecosystem carbon sink capacity by strengthening spatial planning and land-use controls, leveraging the carbon sequestration functions of forests, grasslands, wetlands, oceans, soils, and permafrost to enhance ecosystem carbon sinks.
- Strengthening international cooperation to address climate change and participating in the formulation of international rules and standards.

In the context of these multifaceted strategies, the primary technological pathways for achieving carbon neutrality are illustrated in Figure 1. These pathways form a comprehensive landscape, encompassing critical areas such as Resource Efficiency Improvement (*e.g.*, grid interconnection, energy storage), Energy Decarbonization (*e.g.*, carbon removal and storage), Energy Efficiency Improvement (*e.g.*, circular economy, building and industry efficiency), the transition to a decarbonized Electricity sector (*e.g.*, hydrogen, bioenergy), sustainable Transport (*e.g.*, renewable energy, CCUS), and Nature-Based Climate Change Solutions.

It is important to note that the technologies listed in this figure represent a collection of primary pathways. The overarching process of achieving carbon neutrality is inherently interdisciplinary, relying on extensive collaboration across diverse fields. Any single engineering challenge often depends on contributions from other domains and disciplines. Therefore, as a journal dedicated to the field of carbon neutrality, our scope cannot be limited solely to carbon neutralization technologies themselves. We must also foster dialogue on a broad spectrum of technologies and innovations, from advanced materials and artificial intelligence to social governance and economic modeling, that can contribute at any stage of the carbon neutrality process. This commitment to interdisciplinary integration is exactly the purpose of launching the *Journal of Carbon Neutrality*.

2 Selected scientific topics related to carbon neutrality

Achieving carbon neutrality requires not only the deployment of established large-scale solutions but also deep exploration of emerging, cross-cutting, and often underappreciated scientific frontiers. As examples, the following five topics exemplify areas where innovative research can significantly accelerate the transition to a net-zero future. These selected research topics are intended to illustrate the breadth of carbon neutrality research, and to demonstrate that the *Journal of Carbon Neutrality* welcomes submissions from all scientific endeavors that can contribute to the goal of carbon neutrality.

2.1 Photovoltaics, Energy Storage, and Electric Mobility

The synergy between photovoltaics (PV), energy storage, and electric mobility forms the backbone of a decarbonized energy system. PV provides abundant renewable electricity, yet its intermittent nature necessitates effective storage solutions, including both stationary systems and vehicle-to-grid (V2G) technologies, which enhance grid flexibility and reliability. Electric mobility complements this framework by not only replacing fossil-fuel-powered transport but also serving as a distributed storage resource that further stabilizes the grid. Together, these three interconnected technologies enable deep electrification of end-use sectors and are central to building a new power system dominated by renewables. Research in this triad focuses on improving efficiency, reducing material criticality, extending lifetime, and optimizing system integration to maximize their collective decarbonization impact.

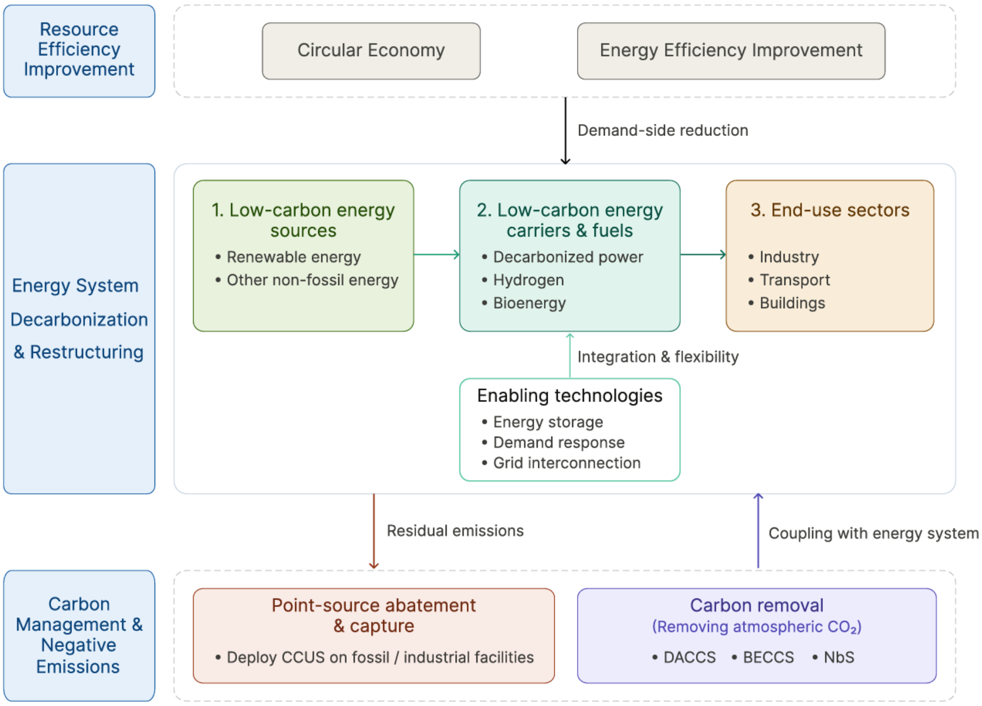

Figure 1. Technical pathways towards carbon neutrality.

2.2 Chemical Valorisation of CO_2

Captured carbon dioxide is often viewed as a waste stream, but it can also be a feedstock. Chemical valorisation of CO_2 involves converting it into valuable products such as synthetic fuels, polymers, chemicals, and building materials through catalytic, electrochemical, or biological processes. This approach not only generates economic incentives for carbon capture but can also create circular carbon cycles where emissions are reused rather than released. While not a substitute for deep emissions reductions, CO_2 valorisation offers a pathway to defossilize hard-to-abate sectors (e.g., chemicals, aviation) and can complement long-term storage strategies. Advancing this field requires breakthroughs in catalyst design, process efficiency, and lifecycle assessment to ensure net climate benefits.

2.3 Mitigation of Contrails

Aviation's climate impact extends beyond its CO_2 emissions. Contrails (*i.e.*, the persistent linear clouds formed by aircraft exhaust) and the cirrus clouds they evolve into exert a substantial warming effect, often comparable to aviation's cumulative CO_2 footprint over time. Mitigation strategies, such as small altitude adjustments to avoid ice-supersaturated regions, can significantly reduce contrail formation with minimal fuel penalty. This topic lies outside traditional carbon-centric technology roadmaps (e.g., sustainable aviation fuels, electric aircraft) but offers a near-term, cost-effective opportunity to reduce aviation's total climate forcing. Research in contrail prediction, operational implementation, and associated trade-offs is critical to realizing this potential. Consequently, the related scientific topics, such as turbulent wake dynamics, particle diffusion, combustion, and multi-phase flows, contribute to advancing carbon neutrality.

2.4 Reduction of Weight and Materials with Low CO_2 Impact

The embodied carbon of materials (*i.e.*, the emissions generated during extraction, production, and manufacturing) accounts for a growing share of global emissions, especially in sectors like construction, automotive, and aerospace. Reducing weight through lightweight materials (e.g., advanced composites, high-strength steels, aluminum alloys) and substituting high-carbon materials with low-CO_2 alternatives (e.g., green steel, low-carbon concrete, bio-based materials) can cut both embodied and operational emissions. Although material efficiency and substitution are often overshadowed by energy-focused solutions, they are indispensable for achieving deep decarbonization across industrial value chains. Key research directions include developing novel low-impact materials, improving recycling and circularity, and integrating material choices into whole-lifecycle optimization frameworks.

2.5 AI for Carbon Footprint Reduction of Healthcare

According to the World Health Organization, up to 5% of global greenhouse gas emissions originate from the health-care sector, contributing to the growing global threat of climate change. Importantly, a large proportion of this footprint arises not only from hospital operations, but also from upstream and downstream activities such as the production, transport, and disposal of pharmaceuticals, medical devices, and other health-care goods and services. This indicates that decarbonization in health care is not merely a matter of improving hospital energy efficiency, but requires a system-level transformation encompassing clinical practice, procurement, logistics, and care delivery pathways.

Artificial intelligence (AI) offers a promising pathway toward such system-level change, owing to its capacity to optimize complex, data-rich processes across the entire health-care value chain. At the facility level, AI-driven approaches can improve energy management and enhance clinical workflow efficiency, directly reducing operational emissions. Along the supply chain, machine-learning-based demand forecasting and inventory optimization can curb overproduction and waste of pharmaceuticals and medical devices, addressing the upstream and downstream sources that dominate the sector's carbon footprint. Furthermore, digital health solutions such as telemedicine, remote monitoring, and virtual triage can reduce patient and staff travel, which represents a meaningful component of health-care-related emissions.

These benefits, however, must be weighed against AI's own environmental cost. Training and operating large-scale models require energy-intensive data centers and digital infrastructure, which carry a non-negligible carbon footprint. The net climate benefit of AI in health care therefore depends on whether the emission reductions it enables across the full delivery life cycle outweigh the additional energy consumption it introduces.

Realizing this potential requires targeted deployment in high-impact areas rather than indiscriminate adoption. Although health care is not typically prioritized in mainstream carbon mitigation roadmaps, its scale and substantial efficiency margins make it a critical area for decarbonization research. Key open challenges include developing sector-specific life-cycle assessment frameworks for AI-assisted health-care systems, establishing emission benchmarks that capture both direct and supply-chain contributions, and designing lightweight AI architectures that minimize computational overhead while preserving clinical utility.

3 Energy harvesting from fluid-structure interaction

In this section, we present recent findings and advances from the authors' research group toward carbon neutrality, with a focus on the technique of energy harvesting from fluid-structure interaction (FSI).

The FSI, also known as aeroelasticity or hydroelasticity depending on the medium, is one of the most fundamental multiphysics phenomena that describes the continuous interplay between fluid flows and deformable or movable structures. When structures are immersed in fluid flows, the fluid forces induce structural deformations or motions, while these structural responses, in turn, modify the flow characteristics. This reciprocal coupling has been extensively studied in aerospace and civil engineering for decades, primarily from the perspective of avoiding catastrophic failures such as flutter and resonance. However, since the early 2000s, researchers have begun to exploit these flow-induced motions as a means of harvesting ambient flow energy, converting what was once considered a design hazard into a sustainable power source [1]. According to the deformability of the harvesting body, FSI energy harvesting mechanisms can be categorized into two principal categories, *i.e.*, solid body mechanisms and flexible body mechanisms.

Solid-body mechanisms represent the classical pathway for FSI energy harvesting, building directly upon decades of vortex-shedding research from Strouhal's 1878 "singing-wire" measurements to the Bénard–von Kármán vortex-street paradigm [2]. In these configurations, the harvesting body remains nominally rigid, and flow energy is extracted through repeatable global motions such as flow-induced vibration (FIV) and flow-induced rotation (FIR). The key advantage of solid-body harvesters lies in their robustness and predictability: hydrodynamic excitation, structural response, and electromechanical conversion can often be parameterized with compact models [3]. This maturity has enabled multiple device archetypes, especially hydrokinetic converters targeting low-to-moderate current speeds [4]. The rigid-body framing also aligns naturally with established vibration machinery design methods, facilitating engineering integration.

However, solid-body mechanisms still have limitations. FIV-based harvesters rely on the lock-in phenomenon for large response amplitudes, which localizes peak performance to a narrow range of reduced velocities [2]. Deployment in variable winds or currents thus faces a fundamental bandwidth challenge. Various extension strategies (geometric shaping, damping tuning, multi-degree-of-freedom designs) have been explored, but these typically introduce trade-offs among bandwidth, peak power, and mechanical complexity [5]. For FIR-based approaches, the engineering penalty shifts toward bearings, frictional losses, and sensitivity to start-up thresholds [6].

Flexible-body mechanisms offer a complementary philosophy: instead of treating large deformations as adverse, flexibility is exploited to unlock large-amplitude limit-cycle motions favorable for direct electromechanical conversion. A representative configuration is the inverted flag, whose flapping dynamics have been characterized extensively [7, 8]. When piezoelectric layers are integrated, cyclic strain yields electrical output, and such configurations have been demonstrated for harvesting ambient wind energy at small scales [9]. Flexible mechanisms also naturally invite array and coupling concepts that can broaden operational regimes through hydrodynamic interference [10]. These characteristics make flexible harvesters attractive for distributed, low-power scenarios aligned with carbon-neutral infrastructure, including self-powered sensing, remote monitoring, and energy-autonomous IoT nodes.

The demerits of flexible-body mechanisms are primarily associated with nonlinearity and durability. Performance depends sensitively on geometric slenderness, mass and stiffness distributions, and inflow conditions, leading to variability across deployments [11]. The large deformations that enable energy conversion also accelerate fatigue, especially when piezoelectric layers introduce electromechanical back-coupling [12]. Moreover, the intrinsically multiphysics nature of the problem means that load-matching and power-conditioning circuitry can meaningfully shift the operating point. While promising for deploy-and-forget microsensor applications, technology readiness remains at an early stage [13]. Within these frameworks, several representative approaches to energy harvesting through FSI are introduced as follows.

3.1 Flow-Induced Rotation (FIR)

FIR refers to the rotational oscillation or continuous spinning of bluff bodies subjected to cross-flow, driven by the asymmetric pressure distribution resulting from periodic vortex shedding. Unlike FIV, where the structural response is typically limited to bounded oscillations, FIR can exhibit a rich variety of dynamic regimes including stable equilibrium, bounded oscillations, chaotic rotations, and sustained autorotation, depending on the Reynolds number, body geometry, and inertial properties of the system.

The square cylinder has emerged as a typical model for studying FIR due to its well-defined geometry and the complex interplay between its sharp corners and the surrounding flow field. Early experimental and numerical investigations by Zaki et al. [14] identified four fundamental response modes: static stability, oscillation, reverse rotation, and autorotation. This classification was subsequently refined and extended by Ryu and Iaccarino [6], who conducted systematic parametric studies and identified six characteristic regimes: stable, small-amplitude oscillation, $\pi/2$-limit oscillation, random rotation, π-limit oscillation, and autorotation, providing a more comprehensive framework for understanding FIR dynamics at moderate Reynolds numbers.

Building upon this foundation, Mou et al. [15] recently conducted an extensive numerical investigation of FIR of square cylinders, expanding the parameter space to include both Reynolds number ($40 \leq \mathrm{Re} \leq 150$) and density ratio ($0.1 \leq \rho \leq 10$) as independent variables. The study employed the immersed boundary method to simulate the two-way coupled fluid-structure interaction, revealing several new phenomena not previously reported in the literature. Notably, two new dynamic regimes were identified: the *transition regime*, characterized by random switching among quasi-$\pi/2$-limit oscillation states with different equilibrium angles, and the *wavy rotation regime*, in which the cylinder exhibits large-angle rotation in one direction followed by small-angle reversal within each period. Additionally, multi-peak sub-regimes were discovered within the π-limit oscillation regime, corresponding to complex energy accumulation processes during the rotational cycle.

A particularly significant finding of Mou et al. [15] is the identification of multi-stable states in certain parameter regions, where the same Reynolds number and density ratio can yield different steady-state regimes depending on initial conditions. The regime map presented in their study provides a valuable design tool for selecting optimal operating points that maximize rotational amplitude while maintaining predictable dynamic behavior.

To complement the numerical investigations, Luo et al. [16] developed an analytical model for the small-amplitude oscillation regime of square cylinders under FIR. Their approach combines an extended free-streamline theory for the inviscid flow field with Blasius boundary layer analysis for the viscous torque calculation, resulting in a free-streamline boundary-layer (FSBL) model. This model successfully explains the mechanism underlying the small-amplitude oscillation regime: the out-of-phase torque that drives the oscillation originates primarily from the imbalanced pressure distribution on the windward face and the asymmetric distribution of pressure and viscous forces on the top and bottom faces. Furthermore, the model provides quantitative predictions of the oscillation frequency and amplitude, validated against immersed boundary method simulations.

The analytical framework developed by Luo et al. [16] also offers insights into the regime boundaries. Specifically, the model predicts a lower Reynolds number limit of approximately 43 for the onset of small-amplitude oscillation, below which the square cylinder returns to a stable equilibrium. At higher Reynolds numbers (beyond approximately 70–80), the boundary layer assumptions underlying the model break down due to the formation of separation bubbles, and the system transitions to more complex regimes such as $\pi/2$-limit oscillation. These theoretical predictions provide guidance for the design of FIR-based energy harvesters, enabling the selection of operating conditions that ensure sustained oscillatory motion.

The broader FIR literature already emphasizes that understanding FIR dynamics can facilitate the design and control of rotation-based energy harvesters [17, 18]. The rotational motion can be directly coupled to electromagnetic generators through appropriate mechanical linkages, potentially achieving higher conversion efficiencies compared to piezoelectric approaches that require cyclic strain. Moreover, the autorotation regime observed at higher Reynolds numbers provides continuous unidirectional rotation, which is ideally suited for conventional rotary generators. For applications in low-power sensing and IoT devices where distributed deployment is essential, the small-amplitude oscillation regime may be combined with piezoelectric transducers to harvest the oscillatory strain energy. The choice between these approaches depends on the specific application requirements, including power output, device size, and environmental conditions.

3.2 Flexible flags

The energy-conversion chain of piezoelectric flags can be viewed as a two-step process: incoming-flow kinetic energy is first transferred into structural strain energy through fluid–structure interaction, and the strain energy is then converted into electrical energy by the piezoelectric layer and its external circuit [12]. Mechanistically, performance is therefore governed by (i) the flow-induced oscillation regime (frequency, amplitude, and spatial strain distribution) and (ii) the electromechanical coupling and load matching that determine how effectively cyclic strain is extracted as useful electrical power.

Regular flag. The classical flag has its leading edge fixed and the trailing edge free. Its large-amplitude response typically arises from flutter-type instability, in which the motion of the flag feeds back positively into the aerodynamic loading and sustains self-excited oscillations. Although this configuration can provide distributed strain suitable for piezoelectric transduction, the onset conditions and the achievable strain distribution are strongly dependent on stiffness, mass ratio, and boundary conditions, which may limit low-speed operability in practical wind/water environments.

Inverted flag. The inverted flag, with a fixed trailing edge and a free leading edge, has received intensive attention because it can exhibit large-amplitude flapping at substantially reduced critical flow velocity compared with the standard flag [7, 8]. From an energy-harvesting perspective, the most valuable operating window is the sustained large-amplitude flapping (limit-cycle oscillation) regime, where cyclic bending produces high strain over repeated cycles and therefore a higher piezoelectric output potential. Importantly, practical designs have already demonstrated power levels on the order of sub-milliwatt to milliwatt in certain operating conditions, suggesting immediate relevance for self-powered sensing at the edge of low-carbon systems [13].

Bluff-body–flag configuration. A complementary single-flag strategy is to place a bluff body upstream (commonly a cylinder or prism) so that the wake unsteadiness acts as an external excitation source for the downstream flag. This forced arrangement can enhance flapping intensity and extend the effective operating window to lower freestream velocities by leveraging wake-induced pressure and velocity fluctuations. From the energy-transduction standpoint, the bluff body primarily amplifies the first step of the conversion chain by increasing the mechanical work input into the flag; the second step is then controlled by piezoelectric coupling, rectification, regulation, and storage elements, which determine how much of the oscillatory electrical output can be converted into usable DC power [19]. Finally, electromechanical feedback should not be overlooked: when the piezoelectric coupling is strong (e.g., for PZT-based devices), the induced voltage can generate an additional internal torque through the inverse piezoelectric effect, and a fully coupled fluid–structure–electric model is often required for predictive design; by contrast, for weaker-coupling polymers such as PVDF, the inverse effect is frequently a secondary correction [20].

Multi-flag arrangement. Scaling flexible-body harvesters toward higher power density naturally motivates multi-flag layouts (side-by-side arrays or tandem/in-line arrangements), where wake interference and structural coupling can yield synchronization, amplitude enhancement, or undesired suppression depending on spacing and stiffness. In this direction, Jia et al. [10] provided a detailed numerical study of dual side-by-side inverted flags as a building block for multi-unit harvesters. By systematically varying bending rigidity, gap distance, and initial conditions, they identified four distinct regimes (straight, flapping, chaotic, and deflected) and further resolved multiple deflected sub-regimes (outside-, inside-, and one-side-deflected) that are inaccessible in single-flag analyses. Of particular relevance to harvesting is the observation that different coupled states (e.g., in-phase versus out-of-phase motion) emerge as the gap distance changes, and that regime transitions can be bistable, implying that initial conditions and perturbations may control whether the system resides in a high-strain (desirable) or low-strain (undesirable) attractor. Their results suggest a practical design message: multi-flag harvesters are not simply two copies of a single device, but a coupled nonlinear system whose accessible oscillation states must be engineered (via spacing, stiffness, and possibly controlled asymmetry) to reliably realize high-amplitude, high-strain motions.

3.3 Fluid-Structure-PiezoElectric Interaction framework

In flexible-body energy harvesters, the transducer is integrated directly onto a compliant structure, enabling the flow to excite large-amplitude deformation that is converted into electricity through distributed strain. A prerequisite for mechanism-driven design is a numerical framework that can resolve the coupled physics across fluid, structure, and circuit without relying on ad hoc decoupling assumptions. In this context, Li et al. [21] proposed a strongly coupled Fluid–Structure–PiezoElectric Interaction (FSPEI) framework that combines a regularized lattice Boltzmann method (LBM) for the fluid, a corotational finite element method (FEM) for slender beams undergoing large displacements/rotations, and a reduced piezoelectric patch model (PEM) for the electrical domain. The central idea is to enforce the no-slip condition through an implicit immersed boundary method (IBM) and to incorporate piezoelectric effects into the beam dynamics via a virtual-work formulation, so that the electromechanical feedback (notably for strongly coupled piezoceramics) is naturally embedded in the time integration. Such a non-staggered strong-coupling strategy is particularly relevant for flexible flags, where the harvested power depends sensitively on phase relations among vortex shedding, structural bending, and electrical loading.

4 Conclusion

This editorial has provided a multidisciplinary perspective on the scientific and technological pathways toward carbon neutrality, emphasizing the critical role of emerging research areas that extend beyond conventional carbon mitigation strategies. Five selected topics (*i.e.*, photovoltaics, energy storage, and electric mobility; chemical CO_2 valorisation; contrail mitigation; lightweight and low-carbon materials; and AI for healthcare decarbonization) illustrate the breadth and depth of innovation required to achieve deep decarbonization across sectors.

Focusing on energy harvesting from fluid-structure interaction, this work has reviewed recent advances in two complementary mechanisms: flow-induced rotation of rigid bodies and flexible flag dynamics. Key contributions include the identification of multi-stable regimes and refined regime maps for square cylinders under FIR, the development of a free-streamline boundary-layer model to explain small-amplitude oscillations, and the demonstration of coupled states in multi-flag configurations that influence energy conversion efficiency. Furthermore, the introduction of a strongly coupled fluid-structure-piezoelectric interaction framework enables predictive modeling of fully coupled electromechanical behavior, facilitating mechanism-driven design.

Together, these findings highlight the potential of FSI-based energy harvesting as a viable approach for powering low-carbon, distributed systems such as self-powered sensors and IoT devices. Continued research in this direction, particularly in system durability, bandwidth enhancement, and integration with real-world energy grids, will be essential to translate these fundamental insights into practical carbon-neutral technologies.

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Not applicable.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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