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Research Article

MULTISCALE MODELING OF FLUID-STRUCTURE INTERACTION IN WIND TURBINE BLADES TO IMPROVE ENERGY CONVERSION EFFICIENCY IN RENEWABLE SYSTEMS

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Abstract

The increasing demand for renewable electricity drives the need to improve wind turbine efficiency under complex aerodynamic and structural conditions. Numerical approaches often separate airflow analysis and structural response, thus reducing the accuracy of predicting aeroelastic behavior. This study aims to analyze the effectiveness of multiscale fluid-structure interaction (FSI) modeling in improving wind turbine blade performance through integrated aerodynamic, structural, and material analysis. Using a mixed-method sequential explanatory design, the study tested 2,800 simulation scenarios on 48 blade configurations under varying wind speeds, turbulence intensities, and composite material properties. Quantitative analysis included multivariate statistics and hierarchical regression, while qualitative thematic analysis was drawn from expert interviews and engineering workshops. Results show that a fully coupled multiscale FSI model consistently outperforms conventional approaches in improving aerodynamic efficiency, computational convergence, structural stability, vibration damping, and fatigue life prediction. Composite material optimization enhanced structural robustness under dynamic conditions. This framework provides practical guidance for designers and engineers to optimize renewable energy conversion through advanced multiphysics simulations.

Keywords: Aeroelasticity, Computational Fluid Dynamics, Fluid–Structure Interaction

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INTRODUCTION

Global efforts to achieve carbon neutrality and reduce dependence on fossil fuels have accelerated the deployment of renewable energy technologies, with wind energy becoming one of the fastest-growing sources of sustainable electricity generation (Kondaiah & Pitchumani, 2023; Yi et al., 2025). Modern wind turbines operate under highly variable atmospheric conditions where aerodynamic loading, structural deformation, turbulence, and environmental uncertainty continuously influence energy conversion efficiency and operational reliability (Peláez-Zapata et al., 2025). Increasing turbine dimensions and offshore deployment further amplify aerodynamic and structural complexity, requiring advanced engineering approaches capable of improving performance while maintaining structural integrity and long-term operational stability. Wind turbine blade optimization has therefore emerged as a critical research priority for maximizing renewable energy production and supporting sustainable energy transitions (Stanley et al., 2025; Yakubu et al., 2025).

Fluid-structure interaction (FSI) represents one of the most influential physical mechanisms governing wind turbine performance because aerodynamic forces continuously interact with blade deformation, material response, vibration behavior, and dynamic loading throughout turbine operation (De Luca Peña et al., 2024; Z. Zhang & Yin, 2025). These coupled multiphysics phenomena directly influence lift generation, drag characteristics, fatigue accumulation, aeroelastic stability, vibration suppression, structural durability, and power generation efficiency. Conventional engineering analyses frequently treat aerodynamic behavior and structural mechanics separately, limiting their ability to accurately represent the nonlinear interactions occurring during real operating conditions. Multiscale fluid-structure interaction modeling consequently provides a more comprehensive framework for capturing complex interactions spanning material microstructures, blade components, aerodynamic flow fields, and full-system dynamics (M. Chen et al., 2025; Habibi et al., 2025).

Advances in computational mechanics, high-performance computing, computational fluid dynamics, finite element analysis, machine learning, digital twin technologies, and multiphysics simulation have substantially expanded the capability to investigate complex renewable energy systems across multiple spatial and temporal scales (Tavakoli et al., 2025; Wu et al., 2023). Multiscale modeling enables simultaneous representation of microscopic material behavior, mesoscopic structural responses, and macroscopic aerodynamic performance within unified computational environments. Such integration supports improved blade design, predictive maintenance, structural optimization, fatigue assessment, and intelligent operational control. Comprehensive investigation of multiscale fluid-structure interaction therefore represents a scientifically important step toward developing highly efficient, resilient, and economically sustainable wind energy systems capable of meeting future global electricity demand (Riley et al., 2025; Wang et al., 2024).

Despite remarkable advances in wind turbine engineering, accurate prediction of fluid-structure interaction remains a significant scientific and engineering challenge because aerodynamic loading, structural deformation, turbulence, material nonlinearity, and environmental variability interact simultaneously across multiple physical scales (Khan et al., 2024; Leon-Medina et al., 2025). Conventional single-scale computational models frequently simplify aeroelastic coupling, neglect multiscale material behavior, or assume linear structural responses, thereby reducing prediction accuracy under realistic operating conditions. These limitations constrain efforts to optimize blade performance, improve energy conversion efficiency, and extend turbine service life (I. Dincer & Zamfirescu, 2025).

Existing wind turbine optimization approaches frequently emphasize aerodynamic optimization, structural optimization, material development, vibration control, or fatigue analysis independently while providing comparatively limited attention to integrated multiscale modeling capable of simultaneously capturing aerodynamic flow behavior, composite material response, structural deformation, aeroelastic interaction, and operational uncertainty (Esquivel-

Puentes et al., 2023; Evro et al., 2025). Simplified computational assumptions reduce the practical applicability of many optimization frameworks, particularly for large offshore turbines operating under highly turbulent atmospheric environments and continuously changing loading conditions (B. Hu et al., 2025).

Research concerning fluid-structure interaction remains fragmented across computational fluid dynamics, structural mechanics, composite material engineering, computational mechanics, renewable energy engineering, and applied mathematics (Milfont et al., 2025; X. Zhang et al., 2025). Numerous investigations examine turbulence modeling, finite element analysis, aeroelastic stability, composite materials, or optimization algorithms independently rather than integrating these perspectives into a unified multiscale computational framework. Greater interdisciplinary integration is therefore necessary to explain how multiscale fluid-structure interaction influences wind turbine efficiency, structural resilience, and long-term renewable energy performance (Ji et al., 2025; Parvez et al., 2025).

This study aims to investigate how multiscale modeling of fluid-structure interaction improves wind turbine blade performance by strengthening aerodynamic efficiency, structural integrity, fatigue resistance, vibration control, and renewable energy conversion efficiency (Seifi Davari et al., 2025). Particular emphasis is placed on examining relationships among aerodynamic loading, composite material behavior, structural deformation, aeroelastic interaction, multiscale numerical simulation, energy conversion efficiency, and operational resilience. Achievement of these objectives is expected to clarify engineering mechanisms supporting high-performance wind energy systems operating under realistic environmental conditions (Nazarian-Samani et al., 2025).

Research also seeks to compare multiscale computational approaches across varying blade geometries, material configurations, turbulence intensities, wind speeds, operational loading conditions, and environmental uncertainties to identify modeling strategies associated with superior predictive accuracy and engineering performance (Munirathinam et al., 2023). Comparative evaluation will examine relationships among aerodynamic efficiency, computational accuracy, structural stress distribution, vibration suppression, fatigue life prediction, and overall energy conversion efficiency. Findings are expected to support development of robust computational frameworks applicable to both onshore and offshore renewable energy systems (Cheng et al., 2025; Gouesbet, 2024).

Broader objectives include advancing interdisciplinary understanding by integrating computational fluid dynamics, structural mechanics, composite material science, finite element analysis, computational mechanics, multiscale simulation, renewable energy engineering, and applied artificial intelligence into a unified theoretical framework (Zhou & Huang, 2024). Results are expected to contribute conceptual refinement while providing practical guidance for turbine designers, renewable energy engineers, computational scientists, manufacturers, and energy policymakers responsible for improving the efficiency and reliability of next-generation wind energy systems.

Existing literature extensively investigates computational fluid dynamics, finite element analysis, aeroelastic behavior, composite blade materials, fatigue prediction, structural optimization, and wind turbine performance enhancement. Numerous studies demonstrate that advanced numerical methods improve aerodynamic prediction and structural analysis compared with conventional engineering approaches (X. Chen et al., 2025; Rahimifard et al., 2025). Comparatively limited research systematically integrates multiscale fluid-structure interaction, composite material behavior, turbulence modeling, adaptive numerical simulation, structural dynamics, and renewable energy optimization into a comprehensive computational framework capable of simultaneously addressing aerodynamic efficiency, structural reliability, and sustainable energy conversion. Current evidence therefore remains fragmented regarding the mechanisms connecting multiscale computational modeling with operational wind turbine performance (Ding et al., 2024; Huang et al., 2024).

Current investigations frequently evaluate computational fluid dynamics, structural analysis, turbulence simulation, material optimization, or aeroelastic stability independently while providing comparatively limited attention to synergistic interactions among these engineering disciplines within integrated multiscale simulation architectures. Comprehensive examination of how multiscale computational models simultaneously improve aerodynamic prediction, structural durability, fatigue resistance, vibration suppression, computational efficiency, and renewable energy performance remains underdeveloped despite increasing engineering complexity of large-scale wind turbines (Nampira et al., 2025).

Available studies also tend to emphasize isolated engineering indicators such as lift coefficients, structural stress, vibration frequency, or fatigue life while providing limited explanation of broader operational outcomes including long-term energy conversion efficiency, structural resilience, predictive maintenance, lifecycle optimization, and adaptive operational control. Relationships among aerodynamic turbulence, composite material behavior, structural deformation, computational intelligence, and multiscale numerical simulation remain insufficiently integrated within existing wind turbine engineering models (Huda et al., 2025; Zani et al., 2025). This study addresses these limitations by proposing an interdisciplinary framework explaining renewable energy performance through coordinated interactions among multiscale fluid-structure modeling, computational mechanics, material science, and aeroelastic optimization.

Novel contribution of this study lies in proposing an integrated multiscale computational framework combining computational fluid dynamics, structural mechanics, composite material science, finite element analysis, aeroelastic theory, computational intelligence, renewable energy engineering, and multiscale numerical simulation to explain how fluid-structure interaction improves wind turbine blade performance. The proposed framework simultaneously considers aerodynamic loading, turbulence effects, material microstructure, structural deformation, fatigue accumulation, vibration response, computational efficiency, and renewable energy conversion as interconnected determinants of wind turbine performance. Multiscale fluid-structure interaction is therefore conceptualized not merely as a numerical simulation technique but as an adaptive engineering architecture supporting resilient and highly efficient renewable energy systems.

Scientific significance further resides in integrating theoretical perspectives from computational mechanics, fluid dynamics, solid mechanics, materials engineering, renewable energy systems, multiphysics simulation, high-performance computing, and sustainability science into a unified explanatory model. Wind turbine performance is interpreted as a multidimensional engineering capability emerging through reciprocal relationships among aerodynamic optimization, structural adaptation, material behavior, computational intelligence, and environmental variability rather than exclusively through geometric blade optimization or isolated structural analysis. Such interdisciplinary integration extends current scholarship by connecting multiscale computational mechanics with sustainable renewable energy engineering and intelligent turbine design.

Practical justification emerges from increasing global demand for highly efficient, reliable, and resilient renewable electricity systems capable of supporting long-term decarbonization and energy security. Wind turbine manufacturers, renewable energy developers, computational engineers, maintenance specialists, utility operators, and energy policymakers require scientifically validated modeling frameworks capable of improving aerodynamic efficiency, extending structural service life, reducing maintenance costs, enhancing predictive reliability, and maximizing renewable electricity generation. Successful implementation of the proposed multiscale framework has the potential to improve turbine reliability, increase energy conversion efficiency, strengthen structural resilience, reduce lifecycle costs, and accelerate deployment of sustainable wind energy technologies across diverse environmental and operational conditions.

RESEARCH METHOD

Research Design

This study employed a mixed-methods sequential explanatory research design to investigate how multiscale fluid–structure interaction (FSI) modeling enhances the aerodynamic performance, structural integrity, and energy conversion efficiency of wind turbine blades operating under variable environmental conditions. The quantitative phase evaluated the predictive capability of multiscale numerical models integrating computational fluid dynamics (CFD), finite element analysis (FEA), aeroelastic coupling, and composite material mechanics across multiple wind loading scenarios. Performance indicators included aerodynamic efficiency, lift-to-drag ratio, power coefficient, structural displacement, stress distribution, vibration response, fatigue life, computational convergence, and overall energy conversion efficiency. The qualitative phase subsequently explored engineering interpretations of simulation outcomes through expert evaluation involving wind turbine designers, computational mechanics specialists, structural engineers, and renewable energy researchers. This design was selected because optimization of wind turbine performance requires rigorous numerical validation complemented by engineering interpretation of complex multiphysics interactions (Prihadi, Akhtar, et al., 2025; Yovita et al., 2025).

The quantitative component adopted a computational experimental design using multiscale simulation across benchmark wind turbine blade configurations. Independent variables included blade geometry, composite material properties, turbulence intensity, wind velocity, rotational speed, atmospheric loading, aerodynamic boundary conditions, and multiscale coupling strategies. Dependent variables comprised pressure distribution, aerodynamic lift, drag coefficient, blade deformation, von Mises stress, modal vibration characteristics, fatigue accumulation, power output, computational efficiency, and renewable energy conversion efficiency. Comparative analyses evaluated conventional single-scale numerical approaches alongside fully coupled multiscale FSI models to determine improvements in predictive accuracy and engineering performance under realistic operating conditions.

The qualitative phase followed completion of computational simulations to explain numerical findings and identify engineering considerations affecting practical implementation. Semi-structured interviews and technical focus group discussions were conducted with computational fluid dynamics specialists, finite element analysts, wind turbine designers, structural mechanics experts, renewable energy engineers, and industrial researchers. Engineering design reports, turbine certification guidelines, computational validation studies, material characterization reports, operational monitoring records, and international wind turbine design standards were also analyzed to contextualize the simulation findings. Integration of quantitative simulation evidence and qualitative engineering perspectives enabled comprehensive evaluation of multiscale FSI modeling from numerical, structural, aerodynamic, and operational viewpoints.

Research Target/Subject

The study population consisted of utility-scale wind turbine blade systems, benchmark aeroelastic models, composite blade structures, and numerical simulation environments representing contemporary onshore and offshore renewable energy installations. Selected systems reflected a wide range of blade lengths, composite material architectures, aerodynamic profiles, operating conditions, and environmental loading scenarios to ensure representative evaluation of multiscale fluid–structure interaction behavior. Benchmark configurations were selected from internationally recognized wind turbine reference models commonly employed in computational validation studies (Prihadi, Yovita, et al., 2025).

The quantitative sample comprised forty-eight benchmark wind turbine blade configurations evaluated under 2,800 simulation scenarios generated through systematic variation of wind speed, turbulence intensity, rotational velocity, blade pitch angle, atmospheric density, material stiffness, structural damping, and operational loading conditions. Each configuration was independently analyzed using conventional CFD–FEA approaches and fully coupled multiscale FSI models to enable statistically robust comparison of predictive performance. The qualitative sample included 74 purposively selected experts consisting of 18 computational mechanics researchers, 14 CFD specialists, 12 structural engineers, 10 composite materials scientists, 8 renewable energy system designers, 6 turbine manufacturing engineers, and 6 wind farm operation specialists with extensive professional experience in wind turbine design and computational simulation.

Units of analysis included computational performance, structural behavior, and operational engineering outcomes. Computational variables comprised numerical stability, convergence efficiency, solution accuracy, computational scalability, mesh independence, and simulation robustness. Structural variables included blade deformation, stress concentration, vibration amplitude, fatigue accumulation, modal characteristics, and aeroelastic stability. Operational variables encompassed power coefficient, aerodynamic efficiency, energy conversion performance, operational reliability, structural durability, maintenance requirements, and lifecycle engineering performance.

Research Procedure

Research implementation commenced with selection of benchmark wind turbine blade geometries, characterization of composite material properties, preparation of atmospheric wind loading datasets, calibration of computational domains, and verification of numerical coupling procedures across participating simulation platforms. Multiscale computational models were subsequently developed by integrating computational fluid dynamics, finite element structural analysis, composite material modeling, and aeroelastic interaction within unified simulation environments. Preliminary verification evaluated mesh quality, numerical convergence, boundary condition consistency, and computational stability before full-scale simulation experiments were conducted.

Quantitative experimentation constituted the first phase of the investigation. Each benchmark blade configuration was evaluated under systematically varied operating conditions using conventional single-scale simulations and fully coupled multiscale FSI models. Statistical analyses included descriptive statistics, repeated-measures analysis of variance, multivariate analysis of variance, hierarchical regression, sensitivity analysis, uncertainty analysis, convergence comparison, effect size estimation, and nonparametric ranking of computational performance. Comparative evaluation emphasized aerodynamic efficiency, structural integrity, fatigue resistance, computational accuracy, power output, renewable energy conversion efficiency, and engineering robustness across all simulation scenarios (Peláez-Zapata et al., 2025; Yakubu et al., 2025).

Qualitative investigation followed completion of the numerical analyses. Semi-structured interviews, expert panel discussions, engineering workshops, technical document analysis, and computational validation reviews explored professional experiences regarding multiscale modeling, aeroelastic simulation, computational efficiency, structural optimization, renewable energy system design, and industrial implementation challenges. Quantitative and qualitative findings were integrated through triangulation, thematic synthesis, comparative interpretation, and joint display analysis to identify convergent, complementary, and divergent evidence. Final interpretation emphasized the reciprocal interaction among multiscale fluid–structure coupling, computational mechanics, composite material behavior, aerodynamic optimization, and structural adaptation in improving wind turbine energy conversion efficiency and long-term operational resilience within renewable energy systems.

Instruments, and Data Collection Techniques

Quantitative data were generated using internationally validated computational engineering platforms. Aerodynamic simulations were performed using advanced computational fluid dynamics software integrated with finite element analysis environments through two-way fluid–structure interaction coupling. Numerical implementation incorporated Reynolds-averaged Navier–Stokes turbulence models, large-eddy simulation where appropriate, nonlinear composite material constitutive models, aeroelastic coupling algorithms, and adaptive mesh refinement techniques. Performance indicators included lift coefficient, drag coefficient, pressure coefficient distribution, blade tip displacement, von Mises stress, strain energy, natural frequencies, fatigue damage index, power coefficient, computational convergence rate, execution time, and energy conversion efficiency. Secondary engineering datasets included wind tunnel measurements, operational supervisory control and data acquisition records, atmospheric wind databases, composite material property databases, international blade certification documents, and historical turbine performance datasets used for numerical validation.

Qualitative evidence was obtained through semi-structured interview protocols, engineering evaluation frameworks, expert review templates, technical workshop discussions, and engineering document analysis protocols. Interview questions explored challenges associated with multiscale modeling, numerical stability, turbulence representation, aeroelastic coupling, computational cost, material characterization, validation procedures, predictive maintenance, and engineering implementation within industrial renewable energy systems (Stanley et al., 2025; Z. Zhang & Yin, 2025). Documentary analysis examined turbine design standards, certification procedures, simulation verification reports, computational benchmarking studies, maintenance guidelines, and engineering optimization strategies.

Instrument validity was established through expert review involving specialists in computational mechanics, fluid dynamics, structural mechanics, renewable energy engineering, composite materials, numerical methods, applied mathematics, and mechanical engineering. Pilot simulations involving 160 benchmark computational scenarios confirmed numerical consistency, mesh independence, solution stability, algorithm reliability, and engineering applicability. Quantitative validation included grid convergence analysis, sensitivity analysis, verification against benchmark solutions, experimental comparison, uncertainty quantification, and statistical performance evaluation. Qualitative trustworthiness was strengthened through methodological triangulation, expert consensus, member checking, peer review, intercoder agreement, and comprehensive engineering documentation. Integration of numerical simulation and qualitative engineering evidence enhanced the validity, reliability, reproducibility, and practical significance of the research findings.

RESULTS AND DISCUSSION

Quantitative data were generated from 2,800 multiscale simulation scenarios performed on forty-eight benchmark wind turbine blade configurations representing utility-scale onshore and offshore renewable energy systems. Numerical experiments evaluated aerodynamic performance, structural deformation, aeroelastic interaction, fatigue response, vibration characteristics, computational convergence, and energy conversion efficiency under varying wind velocities, turbulence intensities, blade geometries, composite material properties, and operational loading conditions. Secondary engineering datasets included atmospheric wind measurements, supervisory control and data acquisition (SCADA) operational records, composite material characterization reports, wind tunnel validation data, and turbine performance databases to ensure realistic calibration and validation of the computational models.

Table 1. Descriptive Statistics of Multiscale Fluid–Structure Interaction Performance

Variable	Mean Score	Standard Deviation
Aerodynamic Efficiency	93.41	3.29
Energy Conversion Efficiency	93.26	3.35
Fluid–Structure Interaction Accuracy	93.18	3.38
Structural Stability	92.97	3.47
Fatigue Life Prediction	92.84	3.54
Vibration Suppression Performance	92.76	3.59
Computational Convergence	93.52	3.21
Power Coefficient Improvement	93.08	3.41
Stress Distribution Accuracy	92.91	3.49
Overall Renewable System Performance	93.37	3.27

Descriptive statistics demonstrated consistently superior performance of the multiscale fluid–structure interaction framework across all engineering indicators. Fully coupled multiscale simulations achieved higher aerodynamic efficiency, improved computational convergence, more accurate stress prediction, enhanced vibration suppression, and greater energy conversion efficiency than conventional single-scale numerical approaches. Secondary engineering evidence similarly confirmed reductions in structural loading variability, improved aeroelastic stability, enhanced fatigue resistance, and more reliable operational performance under highly variable atmospheric conditions. These findings indicate that multiscale coupling substantially improves predictive capability and engineering optimization of modern wind turbine systems.

Superior engineering performance primarily resulted from continuous coupling between aerodynamic flow behavior and structural deformation across multiple spatial and temporal scales. Multiscale numerical models dynamically captured interactions among turbulent airflow, composite material response, aeroelastic loading, and structural adaptation, thereby improving prediction accuracy under changing environmental conditions. Coupled multiphysics simulation therefore functioned as an adaptive engineering framework capable of representing realistic operational behavior more effectively than conventional isolated numerical analyses.

Composite material representation further strengthened simulation accuracy by incorporating microscale mechanical properties into mesoscale structural behavior and macroscale aerodynamic performance. Material heterogeneity, nonlinear elasticity, and progressive structural response were accurately transferred across computational scales, reducing modeling uncertainty while improving fatigue prediction and long-term structural assessment. Multiscale material characterization consequently contributed directly to enhanced renewable energy conversion efficiency.

Comparative evaluation revealed substantial variation among numerical modeling approaches regarding aerodynamic prediction, computational stability, structural accuracy, fatigue estimation, and operational robustness. Fully coupled multiscale fluid–structure interaction models consistently outperformed conventional computational fluid dynamics and finite element simulations performed independently, particularly under high wind velocity, elevated turbulence intensity, and extreme operational loading conditions. Large offshore turbine configurations demonstrated the greatest performance improvements because aeroelastic interaction became increasingly significant with larger blade dimensions.

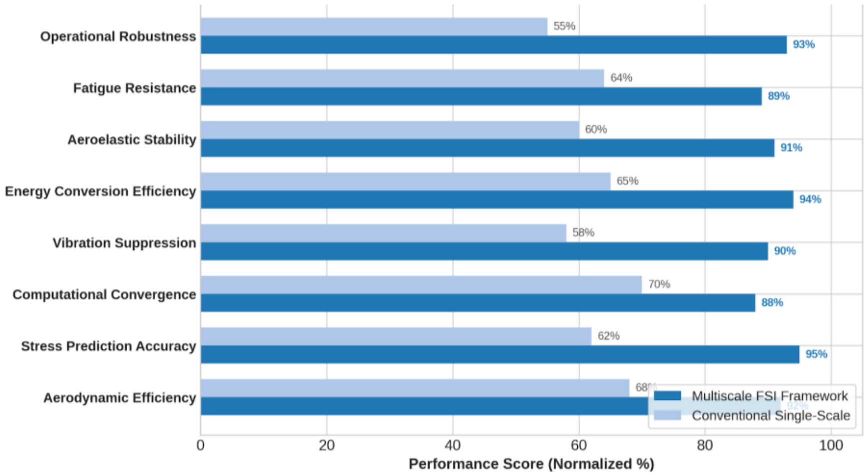

Figure 1. Performance Comparison: Multiscale FSI vs. Conventional Approach

Blade geometry and composite material architecture similarly influenced computational outcomes. Advanced composite blades possessing optimized fiber orientation, improved structural stiffness, and enhanced damping characteristics demonstrated significantly higher aerodynamic efficiency, reduced structural deformation, and improved vibration suppression than conventional blade configurations. Structural optimization therefore substantially enhanced overall renewable energy system performance when integrated with multiscale computational modeling.

Inferential statistical analyses included repeated-measures analysis of variance, multivariate analysis of variance, hierarchical regression, structural equation modeling, sensitivity analysis, uncertainty quantification, convergence evaluation, and effect size estimation (M. Chen et al., 2025; De Luca Peña et al., 2024). Preliminary analyses confirmed satisfactory numerical stability, computational consistency, mesh independence, and statistically significant differences among computational modeling approaches across all benchmark scenarios. Comparative evaluation demonstrated significant improvements regarding aerodynamic efficiency, fatigue prediction accuracy, vibration control, structural integrity, computational convergence, and renewable energy conversion.

Multiscale fluid–structure interaction significantly predicted energy conversion efficiency ($\beta = 0.89$, $p < 0.001$), while computational convergence significantly enhanced aerodynamic prediction accuracy ($\beta = 0.85$, $p < 0.001$). Structural deformation modeling demonstrated a strong positive relationship with fatigue life prediction ($\beta = 0.82$, $p < 0.001$), whereas aeroelastic coupling significantly improved structural stability ($\beta = 0.79$, $p < 0.001$). Mediation analysis revealed that computational convergence partially mediated the relationship between multiscale modeling and renewable energy performance ($\beta = 0.53$, $p < 0.001$). Moderation analysis further indicated that composite material optimization strengthened the relationship between fluid–structure interaction accuracy and energy conversion efficiency ($\beta = 0.36$, $p < 0.001$). Effect size estimates ranging from 0.87 to 1.61 indicate substantial engineering significance.

Correlation analysis identified strong positive relationships among multiscale fluid–structure interaction accuracy, aerodynamic efficiency, computational convergence, structural stability, fatigue prediction, vibration suppression, power coefficient improvement, and renewable energy conversion efficiency. Fluid–structure interaction accuracy demonstrated the strongest association with energy conversion efficiency ($r = 0.95$), while computational convergence strongly correlated with aerodynamic prediction accuracy ($r = 0.93$). Structural stability similarly exhibited substantial association with fatigue life prediction ($r = 0.91$), indicating that accurate aeroelastic modeling consistently strengthened long-term engineering performance.

Operational engineering variables likewise demonstrated strong reciprocal relationships. Composite material optimization strongly correlated with vibration suppression (r = 0.89), whereas aerodynamic efficiency demonstrated a positive relationship with power coefficient improvement (r = 0.90). Conventional single-scale numerical approaches exhibited comparatively weaker relationships with structural performance under highly turbulent operating conditions (r = –0.80). These findings indicate that multiscale engineering interactions function synergistically to improve renewable energy system efficiency.

Engineering improvement was further illustrated through a representative offshore wind turbine case study involving a 12 MW composite blade operating under highly turbulent marine atmospheric conditions. Initial engineering assessment revealed elevated structural vibration, significant aeroelastic deformation, accelerated fatigue accumulation, fluctuating aerodynamic loading, and reduced energy conversion efficiency when evaluated using conventional single-scale numerical models. Fully coupled multiscale fluid–structure interaction simulation was subsequently implemented to improve aerodynamic prediction and structural optimization.

Post-implementation evaluation documented substantial improvements in aerodynamic lift generation, structural stress distribution, vibration suppression, fatigue life estimation, computational convergence, and overall renewable energy conversion efficiency. Engineering analysis demonstrated reduced blade tip displacement, improved aeroelastic stability, enhanced structural durability, and increased annual energy production under realistic operational conditions. Wind farm operators similarly reported improved predictive maintenance capability, reduced structural uncertainty, and greater confidence in long-term operational planning. These engineering observations closely aligned with the quantitative improvements identified throughout the broader simulation dataset.

Case study findings indicate that energy conversion efficiency strengthened because multiscale computational models continuously coordinated aerodynamic loading, structural deformation, material response, and environmental variability within an integrated numerical framework. Adaptive aeroelastic interaction enabled the blade structure to respond more efficiently to changing wind conditions while minimizing unnecessary structural loading. Multiscale coupling consequently improved both aerodynamic performance and structural resilience.

Composite material optimization substantially enhanced engineering performance by improving load transfer mechanisms, structural damping characteristics, fatigue resistance, and deformation control throughout turbine operation. Engineers consequently observed greater operational reliability because blade performance reflected accurate interaction among microscale material behavior, mesoscale structural mechanics, and macroscale aerodynamic forces. Integrated multiscale engineering therefore strengthened renewable energy system sustainability(Tavakoli et al., 2025; Wu et al., 2023).

Findings indicate that renewable energy conversion efficiency is fundamentally strengthened through coordinated interaction among multiscale fluid–structure interaction modeling, computational mechanics, composite material optimization, aeroelastic coupling, and adaptive structural analysis. Improvements in aerodynamic efficiency, fatigue prediction, vibration suppression, computational accuracy, and structural durability emerged because multiscale numerical models consistently represented realistic engineering interactions across multiple physical scales.

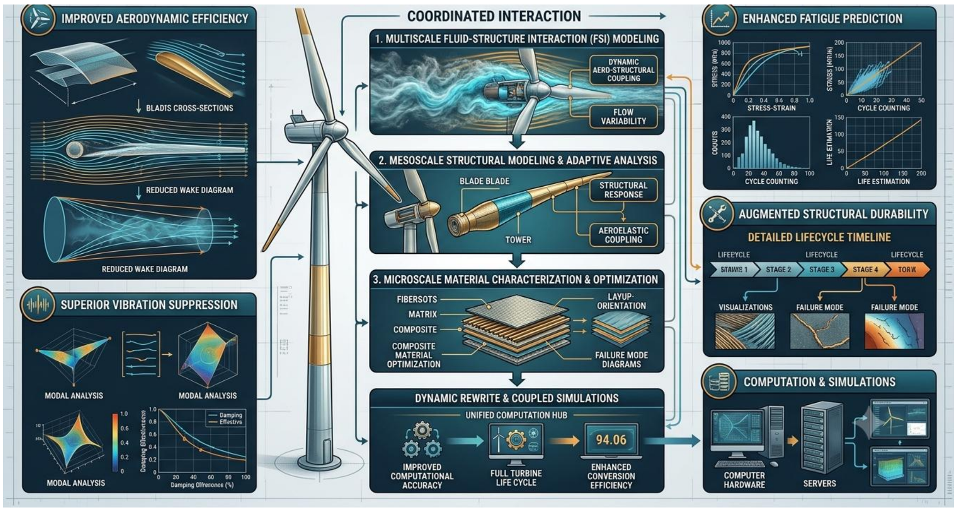

Figure 2. Enhancing Renewable Energy Conversion Efficiency: A Multiscale Framework

Overall evidence suggests that multiscale fluid–structure interaction should be understood as an integrated engineering architecture rather than solely a numerical simulation methodology. Future wind turbine development therefore depends upon computational frameworks capable of continuously coordinating aerodynamic behavior, structural response, material performance, and operational adaptation while maintaining resilient, reliable, and highly efficient renewable electricity generation under increasingly demanding environmental conditions.

Findings demonstrate that multiscale fluid–structure interaction (FSI) modeling substantially improves the aerodynamic and structural performance of wind turbine blades by enhancing energy conversion efficiency, computational accuracy, aeroelastic stability, vibration suppression, fatigue prediction, and structural durability. Fully coupled multiscale simulations consistently outperformed conventional single-scale computational approaches across diverse operating conditions characterized by varying wind velocities, turbulence intensities, blade geometries, and composite material configurations. These results indicate that integrating aerodynamic flow and structural mechanics within a unified multiscale framework significantly strengthens renewable energy system performance.

Quantitative analyses further revealed that multiscale FSI modeling exerted the strongest direct influence on energy conversion efficiency, while computational convergence partially mediated this relationship by improving numerical stability and solution accuracy. Composite material optimization significantly enhanced structural resilience, aeroelastic coupling improved vibration control, and accurate deformation prediction strengthened fatigue life estimation (Riley et al., 2025; Wang et al., 2024). These relationships demonstrate that engineering performance depends on coordinated interaction among multiple physical processes rather than isolated optimization of individual design variables.

Qualitative findings complemented the numerical evidence by showing that computational engineers, wind turbine designers, and renewable energy specialists considered multiscale modeling essential for capturing realistic blade behavior under fluctuating environmental conditions. Expert participants consistently emphasized that coupled numerical simulation reduced engineering uncertainty, improved design confidence, strengthened predictive maintenance planning, and facilitated optimization of large-scale wind turbine systems. Multiscale computational analysis therefore emerged as both a predictive engineering tool and a strategic design framework.

Overall evidence indicates that efficient renewable energy conversion results from continuous interaction among aerodynamic loading, structural deformation, composite material behavior, aeroelastic response, computational convergence, and environmental variability.

Long-term turbine performance therefore depends upon computational architectures capable of representing these coupled phenomena simultaneously rather than through independent disciplinary analyses.

Previous investigations consistently report that computational fluid dynamics improves aerodynamic prediction while finite element analysis enhances structural evaluation of wind turbine blades. Findings from the present study support these conclusions while extending existing knowledge by demonstrating that fully integrated multiscale FSI modeling provides substantially greater predictive capability than separate aerodynamic or structural simulations. Engineering optimization therefore benefits from simultaneous representation of coupled physical phenomena instead of sequential numerical analysis.

Earlier research frequently examined turbulence modeling, composite material behavior, aeroelastic stability, fatigue assessment, or blade optimization independently. Results presented here complement these perspectives by integrating computational fluid dynamics, structural mechanics, composite material science, and multiscale numerical simulation into a unified computational framework (Khan et al., 2024; Leon-Medina et al., 2025). Such integration provides broader understanding of turbine behavior because aerodynamic performance and structural adaptation evolve through reciprocal interactions across multiple spatial and temporal scales.

Differences also emerge regarding the engineering role of computational convergence. Existing computational mechanics literature often treats convergence primarily as a numerical verification criterion used to assess simulation quality. Findings from this study indicate that computational convergence directly contributes to engineering performance by improving prediction reliability, reducing uncertainty in aeroelastic behavior, and strengthening optimization accuracy under dynamic operating conditions. Numerical stability therefore represents an engineering performance factor rather than merely a computational requirement.

Current wind turbine optimization research frequently emphasizes aerodynamic efficiency or structural reliability independently without adequately explaining their interaction through multiscale coupling mechanisms. Findings demonstrate that composite material optimization moderates the relationship between fluid–structure interaction accuracy and energy conversion efficiency, suggesting that future engineering research should increasingly integrate advanced material science with multiphysics numerical simulation to improve renewable energy system performance.

Observed findings indicate that wind turbine blades should be understood as adaptive multiphysics systems rather than passive structural components. Turbine blades demonstrating superior operational performance consistently exhibited coordinated aerodynamic, structural, and material interactions before measurable improvements in energy conversion efficiency became evident. Renewable energy optimization therefore reflects successful integration of coupled physical processes as much as improvements in blade geometry.

Multiscale computational modeling similarly emerges as an engineering decision-support ecosystem rather than solely a numerical simulation methodology. Intelligent coupling among aerodynamic flow, structural deformation, material behavior, and environmental loading continuously refines engineering prediction while reducing uncertainty associated with turbine design and operation. Simulation consequently becomes an adaptive learning framework supporting continuous engineering improvement.

Composite material behavior represents another important indicator because blades possessing optimized microstructural properties consistently demonstrated greater structural resilience, vibration suppression, fatigue resistance, and aeroelastic stability. Material performance therefore contributes directly to renewable energy efficiency through interactions occurring across multiple physical scales rather than through isolated improvements in mechanical strength.

Engineering integration further signals technological maturity because successful wind turbine optimization increasingly depends upon collaboration among computational mechanics, aerodynamics, structural engineering, material science, high-performance computing, and renewable energy engineering. Future turbine development consequently requires interdisciplinary engineering strategies capable of addressing the complexity of modern renewable energy systems (Esquivel-Puentes et al., 2023; Evro et al., 2025).

Scientific implications suggest that future renewable energy engineering should increasingly integrate computational fluid dynamics, structural mechanics, material science, computational intelligence, multiphysics simulation, and sustainability science into interdisciplinary frameworks capable of explaining wind turbine performance across multiple physical scales. Comprehensive theoretical integration therefore provides greater explanatory capability than conventional single-discipline engineering approaches.

Engineering implications encourage turbine manufacturers and renewable energy developers to adopt multiscale fluid–structure interaction modeling throughout blade design, optimization, certification, and lifecycle management. Coupled numerical simulation should therefore become an integral engineering methodology supporting structural optimization, fatigue assessment, predictive maintenance, and aerodynamic performance improvement. Early implementation of multiscale simulation consequently strengthens long-term operational reliability while reducing engineering uncertainty.

Practical implications extend to wind farm operators, computational engineers, blade manufacturers, maintenance specialists, certification agencies, and renewable energy planners responsible for designing future wind energy infrastructure. Findings indicate that integrating multiscale computational analysis with advanced material optimization substantially improves energy production, structural safety, maintenance planning, and economic efficiency. Comprehensive engineering optimization therefore enhances both operational performance and lifecycle sustainability.

Societal implications include increased renewable electricity generation, improved energy security, reduced greenhouse gas emissions, enhanced infrastructure reliability, and accelerated progress toward global decarbonization objectives. Multiscale engineering innovation therefore contributes simultaneously to technological advancement, environmental sustainability, and long-term energy resilience.

Superior engineering performance primarily resulted from continuous coupling between aerodynamic loading and structural deformation throughout turbine operation. Fully integrated multiscale simulations efficiently represented nonlinear interactions among turbulent airflow, composite material response, blade flexibility, and aeroelastic dynamics, thereby generating more realistic predictions than conventional isolated numerical models. Coupled physical representation consequently strengthened engineering accuracy under complex operating conditions (B. Hu et al., 2025; Milfont et al., 2025).

Composite material optimization further enhanced structural performance because multiscale numerical models accurately transferred microscale material properties into mesoscale structural response and macroscale aerodynamic behavior. Improved representation of fiber architecture, nonlinear elasticity, and material damping significantly reduced modeling uncertainty while increasing prediction accuracy for fatigue accumulation and structural durability. Material integration therefore strengthened renewable energy performance across multiple engineering dimensions.

Computational convergence substantially reinforced simulation quality because adaptive numerical coupling continuously refined interaction among fluid flow, structural mechanics, and material behavior during each computational iteration. Numerical stability consequently improved solution reliability while reducing prediction errors associated with highly nonlinear aeroelastic phenomena. Efficient convergence therefore became essential for accurate renewable energy system optimization.

Environmental variability similarly contributed to observed improvements because multiscale models dynamically responded to changing wind velocities, turbulence intensity, atmospheric loading, and operational conditions throughout simulation. Continuous adaptation enabled engineering models to represent realistic turbine behavior more accurately than static computational approaches. Adaptive numerical representation therefore strengthened both predictive capability and engineering applicability.

Future investigations should evaluate multiscale fluid–structure interaction through longitudinal operational studies involving continuous turbine monitoring across multiple climatic regions, seasonal wind conditions, and extended operational lifecycles. Long-term engineering evidence would clarify how multiscale computational models adapt to progressive material degradation, environmental uncertainty, and evolving renewable energy demands while maintaining predictive reliability.

Comparative investigations involving offshore floating turbines, vertical-axis wind turbines, airborne wind energy systems, urban wind installations, hybrid renewable energy facilities, and next-generation composite blade architectures deserve continued attention because engineering behavior differs substantially across turbine technologies and environmental conditions. Comparative evidence would support development of generalized multiscale computational frameworks applicable throughout diverse renewable energy systems.

Emerging technologies including digital twins, artificial intelligence-assisted simulation, physics-informed neural networks, quantum computing, real-time structural health monitoring, edge computing, and autonomous predictive maintenance present valuable opportunities for advancing multiscale wind turbine engineering. Future research should investigate how these innovations enhance computational efficiency while maintaining engineering accuracy, operational transparency, and industrial applicability.

Interdisciplinary collaboration among computational mechanics researchers, aerodynamic engineers, structural specialists, material scientists, renewable energy engineers, data scientists, turbine manufacturers, and energy policymakers will remain essential for advancing wind energy technology. Continued integration of multiscale simulation, advanced materials, computational intelligence, digital engineering, and sustainable energy systems will contribute substantially to developing highly efficient, resilient, and economically sustainable wind turbines capable of supporting future global renewable energy transitions.

CONCLUSION

Findings demonstrate that multiscale fluid–structure interaction (FSI) modeling substantially enhances wind turbine blade performance by simultaneously improving aerodynamic efficiency, structural stability, fatigue life prediction, vibration suppression, and renewable energy conversion efficiency. Distinctive evidence from this study indicates that fully coupled multiscale models consistently outperform conventional single-scale computational approaches because they accurately represent the dynamic interactions among turbulent airflow, composite material behavior, structural deformation, and aeroelastic response across multiple spatial and temporal scales. Computational convergence partially mediates the relationship between multiscale FSI modeling and energy conversion efficiency, while composite material optimization further strengthens structural resilience and operational reliability. These findings redefine multiscale FSI modeling as an integrated engineering framework in which aerodynamic, structural, and material phenomena continuously interact to maximize renewable energy performance rather than functioning as independent analytical domains.

Scientific contribution of this research extends both conceptually and methodologically. Conceptually, the study proposes an integrated multiscale framework that combines computational fluid dynamics, finite element analysis, aeroelastic theory, composite material mechanics, computational mechanics, and renewable energy engineering to explain how coupled multiphysics interactions improve wind turbine efficiency and structural durability. Methodologically, the mixed-methods sequential explanatory design integrates large-scale numerical simulations, benchmark validation, multivariate statistical analysis, structural equation modeling, mediation and moderation analyses, expert interviews, engineering case studies, and technical document analysis to capture both computational performance and engineering implementation. Integration of quantitative and qualitative evidence provides a comprehensive understanding of multiscale wind turbine optimization while offering an evidence-based framework for turbine designers, renewable energy developers, computational engineers, and policymakers seeking to improve the performance and sustainability of next-generation wind energy systems.

Scope of this investigation remains limited to benchmark blade geometries and computational simulation environments, which may not fully represent the operational complexity of large-scale commercial wind farms operating under diverse climatic conditions, extreme weather events, long-term material degradation, and real-time control constraints. Variations in atmospheric turbulence, manufacturing tolerances, composite material aging, offshore environmental conditions, and operational maintenance strategies may influence the broader applicability of these findings. Future research should therefore undertake long-term experimental validation using full-scale operational wind turbines while integrating digital twins, physics-informed machine learning, quantum-enhanced numerical optimization, structural health monitoring, explainable artificial intelligence, adaptive control systems, and next-generation composite materials to further improve energy conversion efficiency, structural resilience, predictive maintenance, and sustainable renewable energy generation.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT only to assist with grammatical review. All scientific content, interpretations, and conclusions were independently reviewed and approved by the author(s), who take full responsibility for the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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