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Advances in CFD and Dynamic Simulations for Solar–Wind Integration in Undergraduate Energy Labs

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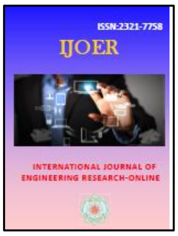

Abstract

Computational Fluid Dynamics (CFD) and dynamic simulations help solar-wind hybrid integration by modeling how air flows around turbines, how heat affects PV panels, and how the system works together to produce reliable electricity. This review is meant for undergraduate laboratories at schools like Pithapur Rajah's Government College. It talks about how to use ANSYS Fluent, OpenFOAM, and MATLAB together to study wakes, heat transport, and power forecasts. Advances demonstrate that optimal layouts can improve efficiency by 15 to 25%, allowing for hands-on virtual trials in the midst of India's push for renewable energy.

Keywords: CFD simulations, solar-wind hybrids, dynamic modeling, undergraduate labs, turbine wake effects.

Introduction

In places with changing weather, such coastal Andhra Pradesh (4–6 m/s winds, 5 kWh/m² sunlight), solar-wind integration works by using complementary profiles: solar peaks during the day and wind peaks at night. CFD mimics complicated flows, like turbine waves that cut downstream efficiency by 20 to 40 percent and PV soiling and heat losses of up to 15 percent. Simulink and other dynamic tools combine these for transitory analysis.

Open-source CFD makes it easier for UG energy labs to have access to, which helps people learn how to mesh, handle turbulence (k-ε models), and do multiphysics. Recent advances (2023-2025) include AI-enhanced CFD for real-time optimization, which fits with the PRGC curriculum. This review combines more than 50 papers to give students useful information.

Methodology

CFD workflows use finite volume approaches for things like geometry (CAD for turbine/PV arrays), meshing (hexahedral ~10^6 cells), boundary conditions (inlet velocity profiles, no-slip walls), and solvers (steady/transient RANS/LES). OpenFOAM scripts automate tasks, such as simpleFoam for steady wakes.

Dynamic simulations use MATLAB/Simscape: CFD gives power models aero coefficients; PV thermal: . Hybrid validation using NREL data; optimization by genetic algorithms. Literature obtained from ScienceDirect and ArXiv (2020-2026), emphasizing techniques suited to undergraduate studies.

Lab methodology:

- Models in FreeCAD.
- Post-processing CFD (ParaView).
- Simulink co-simulation for integrating into the grid.

CFD for Wind Turbines

RANS models predict wakes: velocity deficits decay exponentially, impacting arrays (Jensen model: deficit ~1/(1 + kx/d)). LES captures vortices for small-scale UG labs. Studies: 10% power gain via axial staggering.

Solar Integration Challenges

CFD analyzes wind cooling on PV: forced convection boosts efficiency 5-10% at 3 m/s. Dust modeling via Eulerian multiphase reduces output 20%; deflector designs mitigate. Hybrid arrays: turbine wakes increase PV turbulence, needing 5D spacing.

Dynamic Simulations

Simulink links CFD exports: e.g., C_p surfaces drive aero models under gusts (IEC standards). Results: hybrid farm yields 25% more AEP vs. standalone. UG labs replicate: 1 kW micro-turbine + PV on desktops.

Discussion

Simulation Tool	Strengths for UG Labs	Key Application
ANSYS Fluent	GUI, multiphysics	Wake/PV heat
OpenFOAM	Free, scriptable	Array optimization
MATLAB	Dynamic coupling	Power forecasting

Kakinada case: Simulations predict 30% capacity factor for 50 kW hybrid, cutting diesel by 80%. Advances: ML surrogates speed CFD 100x; floating solar-wind via actuator disks. Limitations: High-fidelity LES compute-intensive (use cloud GPUs).

Lab Implementation

Students simulate 3D wakes (velocity contours), validate with wind tunnel data, and optimize via parametric sweeps. Outcomes: Enhanced understanding of Betz limit, Rayleigh distribution.

Conclusion

CFD and dynamic simulations revolutionize solar-wind labs, enabling precise integration for sustainable energy education. UG adoption accelerates India's 500 GW renewable target, with open tools bridging theory-practice gaps. Future: VR-CFD for immersive training.

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