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ABSTRACT: Tidal power is a predictable marine renewable resource; however, its deliverable output remains strongly constrained by site exclusions, environmental limits, array losses, and distance to the grid. This brief review presents the recent peer-reviewed work on (i) resource potential, (ii) turbine and array technology, and (iii) CFD-based blade/rotor simulation for vertical-axis tidal turbines (VATT). Global assessments suggest an order-of-magnitude harvestable tidal-stream energy of around 1200 TWh per year, while tidal-range atlases report much larger theoretical values, 9220 TWh/y, that are unlikely to be buildable once ecological, social, and infrastructure constraints are applied. For Malaysia, the Straits of Malacca are repeatedly identified as having usable tidal-stream resources, but are more realistically framed for localized, small-scale, or off-grid supply. In contrast, selected Sabah and Sarawak sites exhibit micro-to-small-scale prospects that still require validated hydrodynamics and device-level evidence. In modelling, the straight-bladed (H-type) Darrieus VATT is often highlighted for its scalable geometry and competitive performance in low-to-moderate currents; however, CFD predictions are sensitive to turbulence closure, blockage or confinement, and discretization choices. The literature converges on a defensible ANSYS Fluent workflow using transient sliding-mesh URANS (commonly SST $k-\omega$), explicit grid and time-step independence (preferably via dimensionless criteria rather than more cells), and validation against flume or tunnel datasets. Looking ahead, progress is best accelerated by an integrated pathway that couples realistic resource and array modelling with reliability/maintainability, degradation management, and environmental risk governance to move from promising potential to bankable projects.

KEYWORDS: Tidal Energy, Current Energy, Renewable Energy, CFD,

Introduction:

Tidal power is emerging as a significant marine renewable source due to its high predictability and numerous high-energy coastal hotspots worldwide. Yet translating tidal physics into practical projects remains challenging due to the site-specific nature, uncertainty in converting resources to yields, as well as the cost and reliability requirements of working in the ocean. These challenges are especially prevalent in countries like Malaysia, where tidal potential is available, but profitability is heavily dependent on hydrodynamic conditions, environmental constraints, and distance to the grid.

To ensure the discussion is evidence-based and reproducible, this paper adopts a structured review with a systematic search approach. Scopus and Web of Science were searched for peer-reviewed journal articles on tidal energy potential, tidal stream or tidal range, tidal turbine technology, and VATT CFD modeling using various combinations of corresponding keywords. The screening was performed by applying the inclusion criteria on [i] relevance to global and regional resource assessment methods, [ii] technological development of tidal turbines, and [iii] CFD methodology validation of VATT. The reviewed studies were then composed to summarise three interlinked themes: (i) what global tidal potential is and is not, (ii) technology development routes appropriate for low-to-moderate current sites, and (iii) CFD best practices and pitfalls when simulating VATT blades/rotors with ANSYS Fluent.

Consequently, the objective of this paper is to link resource interrogation to device-level modeling and present a realistic approach that underpins the successful deployment of tidal technology in the future.

1. Tidal Energy Potential

A global cross-resource synthesis suggests that tidal and ocean current resources can also be among the more consistently high-potential offshore renewable energy sources in many parts of the world. However, the results are most useful for screening purposes, as assumptions regarding constraints and extractable fractions differ. (James et al., 2025). Regarding Turbine tidal stream/current energy, in a comprehensive review including technology as well as lifecycle perspective, an order-of-magnitude global harvestable tidal energy of ~1200 TWh/year is being reported, emphasizing, however, that extraction restrictions and environmental constraints array losses among other factors, and distance-to-grid can significantly change the achievable share (Li & Zhu, 2023). For tidal range, recent global reassessment work using a tidal atlas suggests that there is theoretically 9220 TWh/y of extractable energy worldwide, but highlights that this would not be buildable capacity due to ecological, social, and infrastructure considerations (Marti Barclay et al., 2023). Recent comprehensive reviews confirm that the headline global figures shrink markedly as one moves from purely theoretical to practical potential, since site-specific exclusions and impacts overwhelmingly determine feasibility (Chowdhury et al., 2021). Systemic bibliometric evidence suggests that the field has transitioned away from simply reporting resource magnitude to considering integrated planning, which combines resource assessment with site constraints, environmental trade-offs, and system-level design. This transition reflects how global potential is now more likely to be interpreted as a constrained and deployable opportunity (Khojasteh et al., 2023).

Generally, Malaysia's tidal energy potential has been presented in terms of two primary means: tidal-stream (current) extraction and tidal-range (barrage/lagoon) schemes. Hydrodynamic results indicate that the Straits of Malacca (west coast of Peninsular Malaysia) has viable tidal-stream resources. However, as in many regions in the world, it is not expected that a significant proportion will be included in the national energy mix. It is better suited to local, small-scale, or off-grid supply, where predictability has high value (Bonar et al., 2018). Modern Malaysia-focused assessments have reinforced this fact: the nation has numerous potential projects; however, deployment is strongly contingent on local flow speed (which fluctuates widely), bathymetry limitations, grid proximity, and environmental/social acceptance (Abd Rahim et al., 2023).

Regarding East Malaysia, particularly in Sabah and Sarawak, several studies indicate relatively promising sites, particularly in cases where coastal geometry and estuarine inlets permit usable head differences or highly concentrated currents. A tidal-range screening study identified Tanjung Manis as a leading barrage candidate (estimated maximum capacity: 50.7 kW). Kuching Barrage at Pending was also identified as a significant site (up to 33.1 kW). These figures suggest micro-to-small-scale feasibility under the stated assumptions (Samo et al., 2020). On the tidal-stream front, in Malaysia, detailed hydrodynamic modeling work has reported a peak kinetic energy flux of ~0.6 kW/m² at a specific location, justifying the requirement for sufficiently accurate and validated models prior to device design and techno-economic decisions (Ali et al., 2023). Complementing resource assessment, CFD studies at East Malaysian sites (e.g., Sibul, Kota Belud, Pulau Jambongan) report power coefficients above 0.4 across realistic TSR ranges for the assumed inflows. This is encouraging for preliminary design. However, bankable estimates require experimental validation, array/wake simulations, and realistic treatment of blockage and free-surface effects (Loh et al., 2025).

Table 1: Potential sites for tidal energy in Malaysia

Site Location	Estimated Capacity	Resource Type	Reference
Tanjung Manis	~50.7 kW	Tidal Range	(Samo et al., 2020)
Kuching (Pending)	~33.1 kW	Tidal Range	(Samo et al., 2020)
Straits of Malacca	Localized/Small-scale	Tidal Stream	(Bonar et al., 2018)

The numerical models for Malaysia that account for anticipated sea-level rise (e.g., 2060 and 2100 projections) indicate that tidal (and wave) power penetration across the country can change, with some sites exhibiting enhanced power potentials under rising-tide scenarios. This means that long-life marine projects in Malaysia should consider future hydrodynamics in resource assessment and device rating, as well as coastal risk planning, instead of relying solely on realistic hindcasts at present (Yaakop et al., 2025). Overall, the literature suggests a two-step development pathway. First, use targeted hotspot mapping with validated models to identify candidates for pilot demonstrations. Second, plan deployments around local load profiles, such as those in islands, coastal communities, ports, and hybrid microgrids, to maximize the value of predictable tidal generation.

2. Tidal Energy Technology Development

The development of tidal current energy technology is primarily driven by horizontal-axis tidal turbines (HATTs), for which numerous studies have been conducted on rotor design, drivetrain, control methods, and deployment methods (Qian et al., 2019; Qin et al., 2022). Tidal turbines are essentially equivalent to wind turbines in terms of rotor kinematics and fluid dynamic principles. Hence, this section also draws on existing research from the wind turbine field, as much of this knowledge can be directly applied and is critical for improving tidal turbine performance. For low- to medium-current sites, recent studies increasingly highlight the value of vertical-axis tidal turbines (VATTs). The motivation is not necessarily higher peak efficiency than horizontal-axis devices, but rather potential array-level advantages, wake interactions, increased packing density, and improved yield under moderate flow conditions. These benefits may suit sites dominated by non-peak velocities (Ouro et al., 2023). Side-by-side, low-velocity feasibility research highlights that, for devices operating at weak currents, the focus on device selection should be on cut-in/self-start capability, turbulence robustness, and site-specific hydrodynamics, rather than solely relying on nominal peak power coefficient (C_p) values (Fernandez-Jimenez et al., 2021; Satrio & Utama, 2021).

Within the VATT literature, the H-type Darrieus, also known as the straight-blade Darrieus, is a VATT that features simple geometry, can be easily scaled, and can achieve competitive performance in low-to-moderate current regimes, depending on rotor design, TSR, and site turbulence (Grondeau et al., 2019; Zhu et al., 2022). Performance enhancements in low-velocity tidal sites can often be attributed to hydrodynamic enhancement strategies that influence the flow environment or the effective momentum available to the rotor. These include strategies focused on passive flow conditioning and augmentation concepts, ducting options, and multi-rotor arrangements that are designed to harness interaction effects rather than assuming a single rotor geometry will be universally best for all weak-current conditions (Grondeau et al., 2019; Patel et al., 2019).

For single-plane and multi-plane comparisons in VATT, to date, the works presenting bi-plane or multi-plane blade configurations for VATT are limited. Unlike wind turbines, biplane concepts have been explored and demonstrated in a vertical-axis wind turbine (VAWT) as presented by (Oulhaci et al., 2017). These findings further emphasize the high potential of biplane structures as a viable concept for enhancing the performance of small vertical-axis wind turbines, particularly in low to moderate wind velocity levels. Nevertheless, more studies at higher scales and a broader range of tip-speed ratios are necessary. The literature reports for VATT primarily report on the twin-rotor, multi-rotor, and multi-turbine arrays, showing that an increase in total power output in weak flows if spacing and interaction are optimized (Jiang et al., 2024; Ma et al., 2018; Sun et al., 2021).

4. Methodologies to Simulate VATT Using CFD

Many blade-resolved CFD studies of VATTs employ transient incompressible URANS (often with sliding mesh), while alternative reduced-order or hybrid approaches, such as actuator-line-based methods, are also reported, depending on the study objectives and computational constraints. Indeed, this framework generally consists of four main methodological steps: (i) turbulence model choice, (ii) coupling rotating–stationary domains, (iii) determination of a suitable mesh and time step and condition, as well as independence analysis, and (iv) validation towards experimental data. This includes the rotating dynamics, which are typically modelled as a sliding-mesh transient URANS configuration, to account for the unsteady torque ripple and wake development, both of which are key factors in VATT performance (Lei et al., 2017; Marsh et al., 2015).

Beyond the numerical expression, more accurate site-specific hydrodynamic effects are substantially important in performance assessment. In the case of a tidal site, blockage effects and channel confinement can have important effects on both measured and simulated power coefficients, biasing C_p values if not adequately taken into account (Fernandez-Jimenez et al., 2021). As such, in studies on control strategies (e.g., variable-pitch), a blade-resolved URANS approach is usually kept while the analytical focus reverts to C_p fluctuations and torque balance from upstream to downstream half-cycles, as well as thrust ripple behaviour (Delafin et al., 2021).

Another widely reported consideration concerns the sensitivity of simulation outcomes to the choice of turbulence model. It is commonly observed that turbulence model selection has a pronounced influence on the predicted C_p , particularly under dynamic stall and transitional flow regimes characteristic of VAWT/VATT operation. Comparative studies have shown that many commonly used eddy-viscosity models tend to either underpredict or overpredict C_p values and wake recovery, highlighting the need for careful model justification and experimental validation (Darczy et al., 2015; Rezaeiha et al., 2019).

For studies where validation accuracy is prioritised, further refinement of the turbulence modelling approach is often required. In particular, SST $k-\omega$ variants have been shown to provide more reliable predictions than several $k-\epsilon$ and Spalart–Allmaras-type models across typical VAWT operating regimes (Rezaeiha et al., 2019). When higher fidelity is required, particularly to resolve dynamic-stall vortices and large separated structures, hybrid RANS–LES methods such as IDDES can be useful. Some studies report improved C_p and wake-trend predictions relative to baseline URANS. However, the computational cost is substantially higher (Lei et al., 2017). Accordingly, practical CFD studies often adopt a two-stage strategy, in which URANS (e.g., SST $k-\omega$ or transitional SST) is first applied for parametric screening, followed by detailed 3D or hybrid RANS–LES simulations when stall physics are central to the study conclusions (Barnes et al., 2021; Lei et al., 2017).

After CFD simulation, at minimum, CFD papers should report the C_p –TSR curve and both instantaneous and cycle-averaged torque coefficients. They should also quantify torque ripple versus azimuth and hydrodynamic loads (thrust and lateral forces). In addition, include at least one wake metric, such as velocity-deficit profiles, vorticity, or turbulence quantities (Marsh et al., 2015; Rezaeiha et al., 2019; Zhu et al., 2022). For turbine arrays' position, wake interaction, and recovery are treated as primary performance outputs, because they determine how turbines influence one another. The Fluent-based works by (Zhu et al., 2022) study the hydrodynamic performance and wake development of an array comprised of H-Darrius VATT under self-starting conditions and compare the performance between the array and a single stand-alone turbine. In the water-current experiment, (Fernandez-Jimenez et al., 2021) emphasize the need to report the blockage ratio by installing the accelerator and simulating the turbine's open-field condition, as these two conditions will affect the turbine's performance.

Overall numerical accuracy depends less on achieving low residuals and more on demonstrating grid and time-step independence, together with proper validation. Numerical studies on Darrieus CFD recommend dimensionless mesh and time-step criteria rather than simply increasing cell count. The aim is to ensure that near-wall resolution and rotor azimuthal stepping are adequate to capture unsteady loading and separated-flow structures (Balduzzi et al., 2016).

From previous numerical studies on Darrieus turbine CFD, it is known that solution accuracy can be evaluated using grid and time-step independence. Dimensionless discretization criteria have been introduced in this situation to determine whether spatial and temporal resolutions are sufficient to resolve unsteady aerodynamic loading and flow separation. (Balduzzi et al., 2016). The best practice reviews stress that we should explicitly document the domain size and boundary placement, rotating–stationary interface method, near-wall treatment ($y+$ strategy), turbulence-model settings, and mesh or time-step sensitivity plots for C_p and torque ripple, not only one operating point (Balduzzi et al., 2016; Barnes et al., 2021). Validation against experimental flume or tunnel datasets remains the strongest evidence of credibility; for tidal and VATT-like rotors, published studies demonstrate validation of power output, torque fluctuation levels, and mounting forces (Marsh et al., 2015) and stress that, without validation, good-looking C_p curves can still be wrong (Rezaeiha et al., 2019).

Through literature, several recurring methodological limitations are consistently identified and should be carefully avoided. First, exclusive reliance on two-dimensional simulations is insufficient when performance metrics depend on tip-loss effects, strut or arm interactions, and three-dimensional stall phenomena, as multiple studies demonstrate that fully three-dimensional modelling is required to capture certain unsteady and separation-dominated flow behaviours (Lei et al., 2017; Marsh et al., 2015). Second, inadequate computational domain sizing or inappropriate boundary condition placement can lead to artificially inflated power coefficients and distorted wake recovery characteristics, thereby compromising the physical credibility of the results (Barnes et al., 2021). Third, inconsistent definitions of the power coefficient—particularly with respect to reference velocity and swept area under blockage or flow acceleration—have been shown to produce misleadingly high C_p values, limiting comparability across studies (Fernandez-Jimenez et al., 2021). Fourth, the omission of systematic grid and time-step independence assessments remains a well-documented source of numerical uncertainty in Darrieus-type CFD simulations, as key outputs such as torque ripple and dynamic stall dynamics are highly sensitive to spatial and temporal discretisation choices (Balduzzi et al., 2016). Taken together, the literature supports a baseline methodology for VATT simulations in ANSYS Fluent. This includes transient sliding-mesh URANS with the SST $k-\omega$ (or transitional SST) model. It also requires explicit reporting of grid and time-step independence via dimensionless criteria, as well as validation against experimental flume or wind-tunnel data. Where research objectives explicitly involve detailed separated-flow vortex physics or three-

dimensional loading mechanisms, selective extension to fully three-dimensional simulations and hybrid scale-resolving approaches (e.g., IDDES) are commonly adopted.

5. Way forward & strategy to develop robust tidal energy technology

For the provision of robust tidal energy technology to be realized over the coming decade, an integrated pathway is proposed that couples array design and resource modeling, reliability and maintainability, performance degradation management, and governance of environmental risk. At the project level, optimization of turbine-array layouts, for macro- and micro-siting, remains one of the most direct paths to increased energy yield and reduced LCOE but must be implemented with real hydrodynamics, wake effects, and operating constraints rather than idealized uniform-flow assumptions (Stansby & Ouro, 2022; Vennell et al., 2015).

Jordan et al. (2022) show that combining ocean/shallow-water models with analytical wake models (e.g., FLORIS) can strengthen micro-siting outcomes; in their 24-turbine array case study, the proposed micro-sited layout was reported to be ~15.8% more productive than a regular staggered layout (Jordan et al., 2022). Wu et al. (2023) report that optimization frameworks that co-optimize power production and cost (including LCOE) produce layouts with measurable benefits over baseline regular/staggered configurations, with total energy generation increasing by ~16–19% and LCOE decreasing by ~12–15% (Wu et al., 2023). For commercialization, Noble et al. (2024) apply learning-rate (cost learning curve) assumptions in a set of what-if scenarios. They estimate plausible cost-reduction trajectories and the scale of sustained market or policy support needed to close the near-term cost gap. This also helps to de-risk private investment (Noble et al., 2024).

Even when robustness is emphasised in marine technology development, it is ultimately constrained by failure rates, downtime, and the severe degradation environment offshore. For that reason, reliability engineering should be treated as a design driver from the outset, rather than as a post-deployment remedy. Deployment-focused evidence indicates that reliability shortfalls and the associated maintenance burden remain major barriers, strengthening the case for a more systematic treatment of component-level failure modes, logistics, and O&M planning (Walker & Thies, 2021). Among the highest-impact degradation pathways—with direct consequences for performance and lifecycle cost—are biofouling and erosion or damage of blades and composite structures. CFD-based assessments report that biofouling-induced surface roughness can impose a measurable performance penalty, supporting proactive mitigation and management strategies (Song et al., 2020). In parallel, failure-analysis syntheses highlight erosion mechanisms and their structural and hydrodynamic implications, motivating stronger integration of materials selection, protection concepts, and inspection/monitoring practices (Habibi et al., 2025). From an asset-management perspective, condition monitoring and data-driven methods should be strengthened, particularly for detecting or estimating fouling and related deterioration using operational signals and emerging digital-monitoring concepts (Rashid et al., 2023). Drivetrain reliability, including gearbox performance, also motivates maintenance practices and technology choices that reflect marine duty cycles (Li & Zhu, 2022). Beyond technical reliability, robust (or resilient) development should embed environmental monitoring and adaptive management as core workstreams; for example, sonar-based observation campaigns can inform ecological risk understanding and help shape operational and consenting practice (Montabaranom et al., 2025). Taken together, a defensible synthesis is a closed-loop pathway that links validated resource-and-array modelling with reliability-informed design, degradation-aware performance management, and evidence-based environmental monitoring, supported by staged deployment and targeted mechanisms that accelerate learning and cost reduction (Khare & Bhuiyan, 2022).

Conclusion

This review links tidal resource interrogation to device-level modelling and argues that credible tidal development depends on closing the gap between potential on paper and deliverable energy under real constraints. The literature indicates that global figures are useful for screening; however, feasibility is ultimately determined by local exclusions, array losses, environmental trade-offs, and grid proximity. In Malaysia, the most defensible near-term pathway is therefore selective and application-driven: prioritize validated hotspot mapping and target pilot deployments that match local load profiles, such as in islands, coastal communities, ports, and hybrid microgrids, rather than assuming large national-mix contributions. At the technological level, VATT options, particularly straight-bladed Darrieus designs, remain attractive for low-to-moderate currents; however, performance claims must be supported by modeling and experiments that account for confinement, blockage, free-surface effects, and realistic turbulence. For ANSYS Fluent, this review proposes a defensible baseline: transient sliding-mesh URANS with a clearly justified turbulence model (commonly SST $k-\omega$). Grid and time-step independence should be demonstrated using dimensionless criteria, and predictions should be validated against datasets from flumes or tunnels. Without these steps, visually plausible C_p curves can be misleading. Finally, the way forward is best framed as an integrated development loop that couple's resource and array modelling with reliability and maintainability, degradation management, and environmental risk governance, so that engineering design, O&M planning, and consenting evidence mature together toward bankable projects.

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Data Availability

No new data were created or analyzed in this study. Data sharing is not applicable to this article

Conflict of interest

The authors declares that there is no conflict of interest

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