JOURNAL OF PRODUCTION ENGINEERING VOL. 29, NO. 1 (2026)
DOI: 10.24867/JPE-2026-01-032

Original research article

Journal of
Production Engineering

https://jpe.ftn.uns.ac.rs/index.php/jpe
ISSN: 1821-4932 (print), ISSN: 2956-2252 (online)

CFD and FEA-based assessment of an oscillating underwater energy harvester for river flow energy harvesting

Carloandhre Pareja 0000-0001-8236-5019, ***David C. Finger*** * 0000-0003-0678-8946,
Juan Manuel Rosselló 0000-0001-7005-9452

Reykjavík University, Department of Engineering, Menntavegur 2, 102 Reykjavik, Iceland

ABSTRACT

This study investigates the numerical performance of an oscillating underwater energy harvester intended for hydrokinetic energy recovery in river flow environments. The analysed concept is based on an oscillating cylinder developed within the H-HOPE project and designed to convert flow-induced motion into usable mechanical energy. A combined Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) approach was applied to evaluate both the hydrodynamic response of the device and its structural behaviour under simulated operating conditions. The CFD results showed that cylinder diameter has a clear influence on the generated power. The 61 mm cylinder produced an average power output of 3.02 W, whereas the 49 mm cylinder generated 2.05 W, indicating a reduction of approximately 32% for the smaller configuration. The structural analysis showed that the maximum Von Mises stress remained below the yield strength of aluminium 6061, while the obtained safety factor of 2.10 confirmed the mechanical adequacy of the design under the analysed loading conditions. The results indicate that the proposed harvester has potential for small-scale river energy applications, particularly where compact and decentralized renewable energy solutions are required. However, further work should include fatigue assessment, fluid–structure interaction analysis and experimental validation under real river flow conditions.

ARTICLE INFO

Received: 19 February 2026
Revised: 01 May 2026
Accepted: 25 May 2026

KEYWORDS:
Hydrokinetic energy;
Underwater energy harvester;
CFD;
FEA;
Structural analysis.

**Corresponding author's.e-mail: davidf@ru.is*

This paper is an extended version of the conference paper presented at DEMI 2025.

1. INTRODUCTION

The increasing global demand for renewable and decentralized energy sources has encouraged the development of technologies capable of harvesting energy from previously unused or weakly exploited resources. Although solar and wind energy represent the most widely adopted renewable energy technologies, their intermittent nature requires complementary solutions that can provide more predictable and locally available energy generation.
In this context, hydropower remains an important renewable energy source because water flows are generally more stable and predictable than many other renewable resources [3].
In addition to conventional hydropower plants, increasing attention has been directed toward hidden and untapped hydropower opportunities. These opportunities include energy recovery from existing water infrastructure, open channels, irrigation systems, water treatment facilities and river flow environments. The H-HOPE project focuses on the development of technologies for exploiting such hidden hydropower resources, with particular attention to compact energy harvesting devices that can be integrated into existing hydraulic systems [5]. These systems are especially relevant for decentralized applications where small amounts of locally generated energy can support monitoring, control or low-power electronic devices.
Hydrokinetic energy harvesters represent one possible approach for recovering energy from flowing water without the need for large dams or significant civil infrastructure. Instead of relying on large hydraulic heads, these devices use the kinetic energy of moving water. Among different concepts, oscillating underwater energy harvesters are of particular interest because they can

exploit flow-induced vibrations and vortex-related phenomena to convert fluid motion into mechanical energy. Such devices may be suitable for river flow conditions, where continuous water movement can provide a stable source of excitation for energy harvesting.

Within the H-HOPE project, the University of Ljubljana developed a prototype underwater energy harvester based on an oscillating cylinder. The device consists of a mechanical support structure, an oscillating cylindrical element, a power transmission mechanism and control components. During operation, the cylinder interacts with the incoming river flow, and the resulting oscillatory motion can be transferred through the mechanical system toward energy conversion. The performance of such a device depends strongly on the interaction between the fluid flow, cylinder geometry, oscillation characteristics and structural response.

For this reason, numerical modelling represents an important step in the design and evaluation of hydrokinetic energy harvesters. Computational Fluid Dynamics (CFD) enables the analysis of flow behaviour around the oscillating cylinder, including velocity fields, pressure distribution, turbulence intensity, vortex shedding and hydrodynamic forces. At the same time, Finite Element Analysis (FEA) allows the evaluation of structural integrity, stress distribution, deformation and safety factor under operating loads. The combined use of CFD and FEA provides a more complete understanding of both the hydrodynamic efficiency and mechanical reliability of the device [2], [6].

Previous studies have shown that small-scale hydrokinetic devices require careful optimization of geometry, flow conditions and structural design in order to achieve acceptable performance and long-term reliability [2], [7]. In addition, turbulence modelling is particularly important when analysing flow-induced vibration and separated flow around cylindrical bodies. The SST k-ω turbulence model is commonly used for such applications because it provides good accuracy in near-wall regions and separated flows [8]. Therefore, an integrated numerical approach is suitable for assessing the behaviour of oscillating underwater harvesters before experimental or field testing.

The aim of this paper is to evaluate the hydrodynamic and structural performance of an oscillating underwater energy harvester intended for river flow applications. The study combines CFD simulations and FEA to estimate power output, analyse the influence of cylinder diameter and assess structural reliability under simulated operating conditions. In addition, the paper presents a flexible CFD–FEA modelling framework that can be used for future modifications of geometry and operating parameters, supporting further development and optimization of underwater hydrokinetic energy harvesters.

2. METHODOLOGY

The methodology used in this study was based on a combined numerical approach that included Computational Fluid Dynamics (CFD), power output estimation and Finite Element Analysis (FEA). This approach was selected in order to evaluate both the hydrodynamic performance and the structural reliability of the oscillating underwater energy harvester under simulated river flow conditions. The CFD analysis was used to determine the flow behaviour around the oscillating cylinder and to calculate the hydrodynamic forces acting on the device. These forces were then used to estimate the mechanical power output and to define the loading conditions for the structural analysis.

2.1 CFD Model Setup

Computational simulations were performed using ANSYS Fluent to analyse the hydrodynamic behaviour of the oscillating cylinder in a confined flow domain. Two-dimensional and three-dimensional numerical models were developed to represent the energy harvester under river flow conditions. The two-dimensional model was mainly used to simulate the sinusoidal oscillation of the cylinder by applying a dynamic mesh, while the three-dimensional model used an overset mesh approach to account for the flow interaction around the full geometry.

The inlet flow velocity was set to 1 m/s, while the prescribed oscillation frequency of the cylinder was 3.28 Hz. These values were selected to represent the operating conditions considered in the numerical analysis. The CFD model was designed to capture unsteady turbulent flow phenomena around the oscillating cylinder, including vortex shedding, pressure fluctuations and changes in lift and drag forces during the oscillation cycle.

The SST k-ω turbulence model was applied because it is suitable for resolving near-wall regions and separated flow, which are important in the analysis of flow-induced vibration around cylindrical bodies [8]. In addition, a Volume of Fluid (VOF) multiphase model was used to represent the interaction between water and air near the free surface. The computational domain was meshed with refined zones around the cylinder and in the wake region in order to improve the resolution of vortex structures and turbulent flow behaviour.

Boundary conditions included a uniform velocity inlet, pressure outlet, symmetry conditions on the lateral boundaries and no-slip conditions on solid surfaces. The free surface was treated through the pressure boundary condition in order to include hydrostatic effects. Transient simulations were performed with a time step of 1×10^{-5} s and a total simulation time of 5 s, allowing several oscillation cycles to be captured. The convergence criteria for continuity and momentum equations were set to 1×10^{-6}.

The hydrodynamic response was analysed using velocity contours, streamline plots, dynamic pressure fields and turbulence intensity distributions. Lift and drag forces were extracted from the cylinder surface and used for further power output estimation. The comparison was performed for two cylinder diameters, 61 mm and 49 mm, under the same flow and oscillation conditions.

2.2 Power Output Estimation

The power output of the device was estimated using a time-dependent energy-based calculation. Instead of applying only a simplified analytical expression, the instantaneous mechanical energy contribution was calculated at each simulation time step based on the hydrodynamic force and the prescribed oscillation velocity.

At each time step, the vertical hydrodynamic force acting on the cylinder was obtained from the CFD results, while the vertical velocity of the oscillating cylinder was defined through the sinusoidal motion. The instantaneous energy contribution was calculated according to Equation (1):

$$E_{(i)} = F_{R(i)} \cdot V_{(i)} \cdot \Delta t \qquad (1)$$

where $E_{(i)}$ is the instantaneous energy at time step i, $F_{R(i)}$ is the vertical hydrodynamic force acting on the cylinder, $V_{(i)}$ is the vertical velocity of the cylinder, and Δt is the simulation time step.

The total mechanical energy generated during one oscillation cycle was then obtained by summing the instantaneous energy values over the analysed time interval, as given in Equation (2):

$$P = \sum_{i=0}^{n} E_{(i)} \qquad (2)$$

This procedure enabled the comparison of the energy harvesting performance of the two analysed cylinder diameters under identical flow conditions.

2.3 Structural Analysis

The structural analysis was performed using the ANSYS Static Structural module in order to evaluate the mechanical behaviour of the energy harvester under hydrodynamic loading. The purpose of this analysis was to determine whether the main structural components could withstand the applied loads without yielding or excessive deformation.

A three-dimensional model of the cylinder and supporting frame was used for the analysis. Aluminium 6061 was selected as the structural material because of its favourable strength-to-weight ratio and corrosion resistance in freshwater environments. The material properties, including Young's modulus, Poisson's ratio and yield strength, were assigned according to standard material data.

The pressure field obtained from the CFD analysis was transferred to the structural model as a distributed load acting on the cylinder and supporting components. Boundary conditions were defined to reproduce the expected operating constraints of the device. Fixed supports were applied to the lower rods, displacement supports were applied to the upper rods, and hydrodynamic loading was applied around the cylinder model, as shown in Figure 1.

A tetrahedral mesh with local refinement was generated in regions where stress concentrations were expected, particularly near joints, fillets and connection points. The structural response was evaluated using three main indicators: Von Mises stress, total deformation and factor of safety. Von Mises stress was used to assess the risk of yielding, total deformation was used to evaluate geometric stability, and the safety factor was used to determine the reliability of the design under the analysed loading conditions.

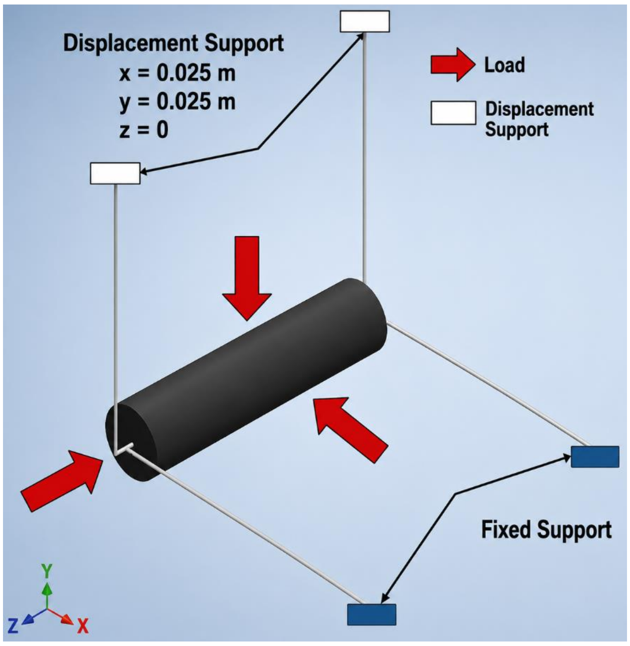

Fig. 1 Collector cylinder with supports and applied loads.

3. RESULTS

3.1 Hydrodynamic Performance

The hydrodynamic simulations provided insight into the flow behaviour around the oscillating cylinder and enabled the estimation of the energy harvesting potential of the device. Under the analysed river flow conditions, the Reynolds number was approximately 197,325, indicating that the flow regime was turbulent. The three-dimensional CFD results showed a maximum dynamic pressure of 1.66 kPa, a peak velocity of 1.72 m/s during the oscillation cycle, and a turbulence intensity of 8.86% at time step 420, corresponding to t=4.5064 s.

The flow visualizations confirmed the presence of periodic vortex shedding and unsteady flow structures around the oscillating cylinder. As shown in Figure 2a, the velocity magnitude distribution indicates flow acceleration around the cylinder and the formation of a lower-velocity wake region downstream.

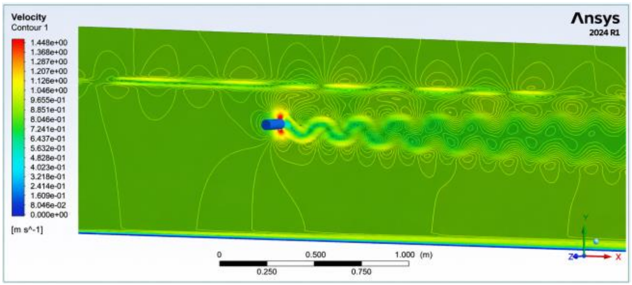

Fig. 2a Velocity magnitude distribution around the oscillating cylinder.

Figure 2b presents the dynamic pressure distribution, where higher pressure values occur near the front side of the cylinder due to the impact of the incoming flow. The turbulence intensity field shown in Figure 2c indicates increased turbulence in the shear layers and wake region behind the cylinder. Together, these results show that the main energy conversion region is located around the cylinder periphery and in the near-wake zone.

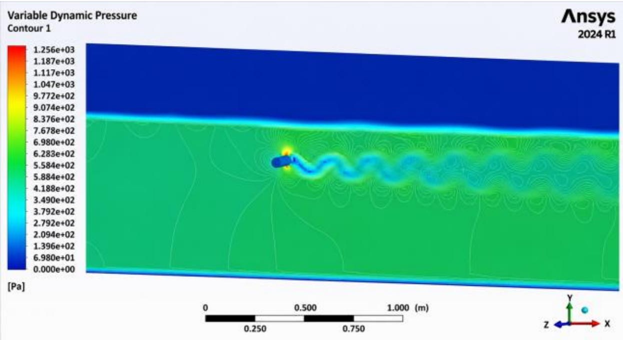

Fig. 2b Dynamic pressure distribution around the oscillating cylinder.

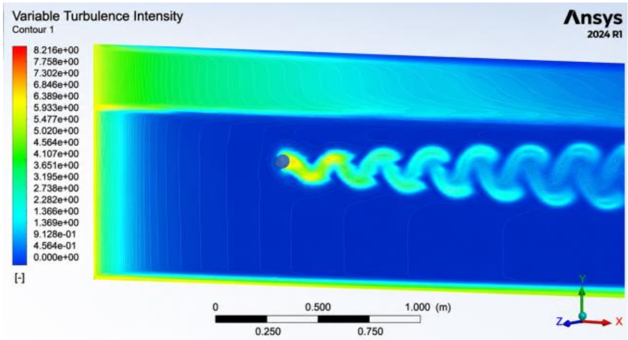

Fig. 2c Turbulence intensity distribution around the oscillating cylinder.

The power output was calculated using the hydrodynamic forces obtained from the CFD simulations and the instantaneous velocity profile of the prescribed oscillating motion. The comparison between the two analysed cylinder diameters showed that the larger cylinder produced higher power output under the same flow and oscillation conditions. As presented in Table 1, the 61 mm cylinder generated an average power of 3.0206 W, while the 49 mm cylinder generated an average power of 2.0501 W.

Table 1 – *Power comparison between 61 mm and 49 mm cylinders.*

Time (s)	Cylinder 61 mm (W)	Cylinder 49 mm (W)
1	3.0474	2.0721
2	3.1643	2.1477
3	2.8306	1.9288
4	3.0745	2.0825
5	2.9861	2.0193
Average	**3.0206**	**2.0501**

The results indicate that reducing the cylinder diameter from 61 mm to 49 mm caused a decrease in average power output of approximately 32%. This confirms that cylinder diameter has a significant influence on the hydrodynamic response and energy harvesting performance of the device. The larger cylinder produced stronger interaction with the flow and generated higher mechanical energy during the oscillation cycle.

3.2 Structural Performance

The structural analysis was carried out to evaluate the mechanical reliability of the device under the hydrodynamic loading conditions obtained from the CFD model. The maximum Von Mises stress reached 133.25 MPa, which is below the yield strength of aluminium 6061. This indicates that the analysed structure remains within the elastic range under the simulated operating conditions. The distribution of Von Mises stress is presented in Figure 3. The highest stress values were concentrated in the load-bearing regions of the support structure, while the remaining parts of the model showed lower stress levels. The calculated safety factor was 2.10, confirming that the design has an acceptable margin of safety for the analysed loading case.

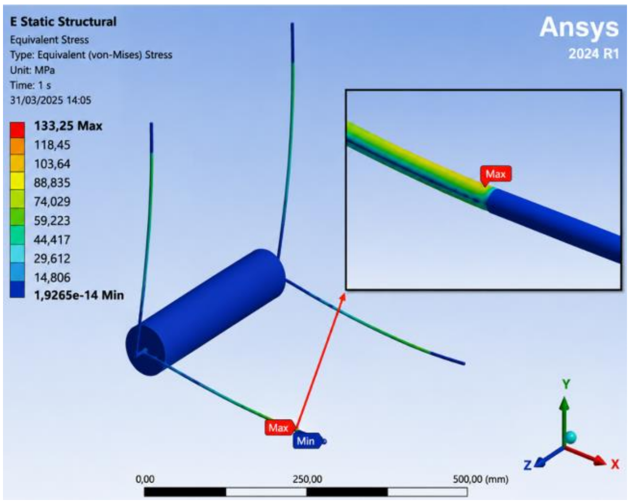

Fig. 3 Von Mises stress distribution over the cylinder model.

The deformation analysis showed that the maximum total displacement occurred on the upper rods. In the original simulation, the total deformation reached approximately 33 mm due to the applied displacement support conditions. However, the deformation caused by stress alone was estimated to be around 11 mm, as shown in Figure 4.

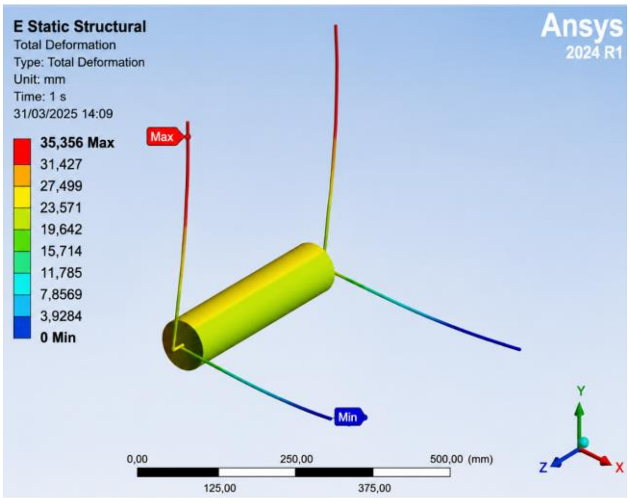

Fig. 4 Total deformation of the cylinder model.

Although the obtained stress values and safety factor indicate that the structure is mechanically reliable under the analysed conditions, the cyclic motion of the oscillating cylinder may lead to fatigue effects in the support rods, particularly in the lower support elements. Therefore, a fatigue analysis should be included in future work in order to evaluate the long-term durability of the device under repeated oscillatory loading.

4. DISCUSSION

The obtained results confirm that the analysed oscillating underwater energy harvester has promising potential for small-scale hydrokinetic energy recovery under river flow conditions. The CFD simulations showed that the device operates in a turbulent flow regime, with clearly developed vortex shedding and unsteady hydrodynamic loading around the oscillating cylinder. These flow characteristics are important because they directly influence the lift and drag forces acting on the cylinder and, consequently, the mechanical energy that can be extracted from the flow.

The comparison between the two cylinder diameters shows that geometry has a significant influence on energy harvesting performance. The 61 mm cylinder generated an average power output of 3.0206 W, while the 49 mm cylinder produced 2.0501 W under the same flow and oscillation conditions.

This reduction of approximately 32 % indicates that even relatively small changes in cylinder diameter can noticeably affect the hydrodynamic response of the system. Therefore, cylinder geometry and oscillation parameters should be carefully optimized in future designs.

The structural results indicate that the proposed design can withstand the analysed hydrodynamic loading conditions. The maximum Von Mises stress of 133.25 MPa remained below the yield strength of aluminium 6061, while the obtained safety factor of 2.10 confirms acceptable mechanical reliability for the simulated case. These findings suggest that the current design is structurally adequate under the analysed operating conditions.

However, the deformation results and the cyclic nature of the cylinder motion indicate that long-term durability should be examined in more detail. Although the stress levels are below the material yield limit, repeated oscillatory loading may cause fatigue damage, particularly in the support rods. For this reason, fatigue analysis represents an important next step before practical deployment or field testing.

The study also highlights several limitations of the current numerical approach. The simulations were performed under fixed flow conditions and with prescribed cylinder motion, which simplifies the real interaction between the fluid and the structure. In real river environments, flow velocity, turbulence intensity, water level and debris interaction may vary over time. Therefore, future models should include fluid–structure interaction, damping effects and more realistic boundary conditions in order to better represent the actual operating behaviour of the device.

Overall, the combined CFD–FEA approach provides a useful framework for evaluating both hydrodynamic performance and structural reliability of oscillating underwater energy harvesters. The developed modelling setup enables future modifications of geometry, material properties and flow conditions, making it suitable for further optimization of similar hydrokinetic devices. In this sense, the presented analysis represents an important step toward the development of compact and decentralized energy harvesting systems for river flow applications. The main numerical findings obtained from the CFD and FEA analyses are summarized in Figure 5.

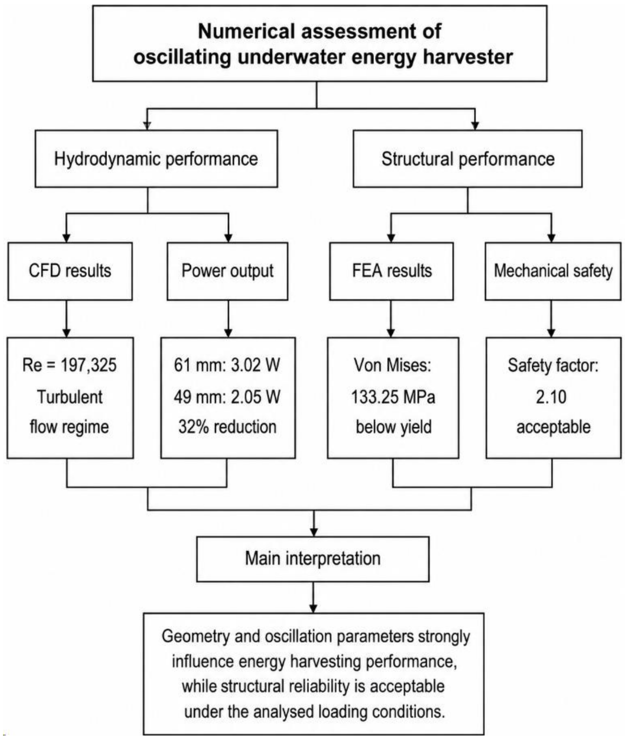

Fig. 5 Summary of the main numerical assessment results for the oscillating underwater energy harvester.

5. CONCLUSIONS

This paper presented a numerical assessment of an oscillating underwater energy harvester intended for hydrokinetic energy recovery under river flow conditions. The study combined CFD and FEA simulations in order to evaluate both the hydrodynamic behaviour and the structural reliability of the proposed device.

The main contribution of the work is the development and application of an integrated CFD–FEA modelling approach that enables the analysis of energy harvesting performance and mechanical response within the same design framework. This approach can be used for future modifications of device geometry, flow parameters and structural configuration, which is important for the further development of compact hydrokinetic energy harvesters.

The results confirmed that the larger cylinder diameter provided better energy harvesting performance. The 61 mm cylinder generated an average power output of 3.0206 W, while the 49 mm cylinder generated 2.0501 W under the same flow conditions. The structural analysis showed that the maximum Von Mises stress remained below the yield strength of aluminium 6061, with a safety factor of 2.10, indicating that the design is mechanically acceptable for the analysed loading case.

Although the obtained results are promising, further research is required before practical implementation. Future work should include fatigue analysis, fluid–structure interaction modelling, damping optimization, material improvements and experimental validation under real river flow conditions. These steps are necessary to confirm long-term durability, improve energy conversion efficiency and support the development of reliable decentralized hydrokinetic energy harvesting systems.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's DG RTD - Horizon Europe research and innovation programme under Grant Agreement No. 101084362. This work was also supported by funding from the Erasmus+ Higher Education Mobility Agreement.

REFERENCES

[1] Alteyeb, A., & Jolgaf, A. (2017). Structural Stress Analysis in Hydrokinetic Energy Systems. Journal of Ocean Engineering, 138: 45–56.

[2] Alvear, D., Hatem, M., & Qasim, H. (2021). Simulation of hydrodynamic performance of small-scale hydrokinetic devices. Renewable Energy, 179: 1212–1226.

[3] Brook, B., Hansen, J., & Smith, P. (2014). Variability and Intermittency in Renewable Energy Systems. Energy Policy, 65: 25–32.

[4] Cengel, Y. A., & Cimbala, J. M. (2004). Fluid Mechanics: Fundamentals and Applications. McGraw-Hill Education.

[5] H-Hope Project. (2024). Hidden and Untapped Hydropower Opportunities. Retrieved March 20, 2025, from https://www.h-hope.eu

[6] Katsidoniotaki, E., Tanwar, N., et al. (2023). CFD modeling of wave-structure interaction for energy extraction. Ocean Engineering, 266: 113123.

[7] Lam, W., & Shamsuddin, A. H. (2013). Foundation Technologies for River Energy Converters. Renewable and Sustainable Energy Reviews, 25: 398–408.

[8] Wilcox, D. C. (2008). Formulation of the k-ω Turbulence Model Revisited. AIAA Journal, 46(11): 2823–2838.