

Modelling of biological impacts of contra-rotating propeller reversible pump turbines on migratory fishes

Miccoli, A.; De Luca, A.; Marcelli, M.; Joseph, M.; Zangeneh, M.; Bricker, J.; Peviani, M.; Scapigliati, G.

DOI

[10.1016/j.joes.2025.08.002](https://doi.org/10.1016/j.joes.2025.08.002)

Publication date

2025

Document Version

Final published version

Published in

Journal of Ocean Engineering and Science

Citation (APA)

Miccoli, A., De Luca, A., Marcelli, M., Joseph, M., Zangeneh, M., Bricker, J., Peviani, M., & Scapigliati, G. (2025). Modelling of biological impacts of contra-rotating propeller reversible pump turbines on migratory fishes. *Journal of Ocean Engineering and Science*, 10(6), 1061-1069.
<https://doi.org/10.1016/j.joes.2025.08.002>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.



Contents lists available at ScienceDirect

Journal of Ocean Engineering and Science

journal homepage: www.elsevier.com/locate/joes

Research Paper

Modelling of biological impacts of contra-rotating propeller reversible pump turbines on migratory fishes

A Miccoli^{a,*}, A De Luca^b, M Marcelli^c, M Joseph^d, M Zangeneh^e, J Bricker^{f,g}, M Peviani^h, G Scapiati^b^a National Research Council, Institute for Marine Biological Resources and Biotechnology (IRBIM), 60125 Ancona, Italy^b Department for Innovation in Biological, Agro-Food and Forest Systems, University of Tuscia, Largo dell'Università, 01100 Viterbo, Italy^c Department of Ecological and Biological Sciences, University of Tuscia, Largo dell'Università, 01100 Viterbo, Italy^d Advanced Design Technology Ltd., London, WC1 × 8NH, UK^e Department of Mechanical Engineering, University College London, London WC1E 6BT, UK^f Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2628 CN Delft, The Netherlands^g Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109, USA^h External Expert in Hydropower and Marine Energy, Viterbo, Italy

ARTICLE INFO

Keywords:

Hydropower
Fish passage
Contra-rotating turbines
Computational fluid dynamics
Biological performance assessment
Hydropower-induced stress assessment

ABSTRACT

Hydropower plays a critical role in global renewable energy production, yet its environmental impacts on aquatic ecosystems remain a concern. This study investigates the biological impacts of Shaft-Driven Variable-Speed Contra-Rotating Propeller Reversible Pump Turbines (SDCRRPTs) on fish populations, using Atlantic salmon (*Salmo salar*) and European eel (*anguilla*) as experimental models. These species present critical ecological and conservation traits, making them ideal models for assessing hydropower-induced stressors such as rapid decompression, shear, collision, and turbulence. Through Computational Fluid Dynamics (CFD) simulations and the Biological Performance Assessment (BioPA) tool, two SDCRRPT prototypes were evaluated under varying operating conditions. Results indicate that rapid decompression posed minimal risks, while shear stress was the primary cause of mortality for salmon, and collision effects were moderate but species-dependent. The optimized turbine design (Prototype 1) demonstrated improvements in adult fish passage safety compared to the initial design, particularly for eels, yet persistent vulnerabilities highlight the need for further refinements and protective measures, such as physical, mechanical or sensory behavioral barriers combined with bypass systems, to mitigate unavoidable mortality risks during turbine passage. The findings highlight the potential for species-specific design optimization to balance ecological conservation with sustainable energy production. This work underscores the importance of integrating environmental considerations into hydropower technologies to support the EU's decarbonization goals while safeguarding aquatic biodiversity.

1. Introduction

Climate change effects, including rising temperatures, ocean acidification and sea level rise, together with the EU policy concerning the decarbonization of the electric system, is fueling interest in the use of marine renewable energy devices. Of these, hydropower contributes a major fraction of the worldwide renewable effort, having increased by almost 70 TWh in 2022, reaching 4300 TWh [1], and presents a viable path for the sustainable production of electricity. Therefore, studies aimed at elucidating the actual impacts that Pumped Hydro System (PHS) plants impose on both the abiotic and biotic components of

aquatic environments, are essential [2]. The eleven descriptors encompassed within the 2008/56/EC Marine Strategy Framework Directive (MSFD) outlines a preliminary assessment of the physical damages and biological disturbance deriving from installation, operation and decommissioning of hydropower-related devices [3]: these include Descriptors 1 (Biodiversity), 3 (Commercial Fish and shellfish), 6 (Sea-floor integrity), 7 (Hydrographical conditions), 8 (Contaminants) and 11 (Energy including underwater noise). Fish communities fall under the umbrella of descriptors 1 and 3, with reference to the biological disturbance pressure from Annex III of the MSFD.

So far, research has mainly focused on examining fish injury and

* Corresponding author.

E-mail address: andrea.miccoli@cnr.it (A. Miccoli).<https://doi.org/10.1016/j.joes.2025.08.002>

Received 24 January 2025; Received in revised form 28 July 2025; Accepted 5 August 2025

Available online 6 August 2025

2468-0133/© 2025 Shanghai Jiaotong University.

<http://creativecommons.org/licenses/by-nc-nd/4.0/>.

Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

mortality extent caused by traditional turbine designs such as Francis and Kaplan turbines. These investigations have clarified important variables influencing fish mortality including blade geometry (e.g. leading edge thickness, shape and velocity) and turbine operating conditions, which determine the major hydropower stress mechanisms (i.e. water pressure change, cavitation, fluid shear stress, turbulence and collision). The severity of such stressors is further determined by anatomical and behavioral traits of different fish species, which emphasizes the necessity for species-specific evaluations or, when this is not a viable option, the exploitation of surrogate species based on evolutionary (e.g. [4]), morphological (i.e. body shape), anatomical (i.e. physostomes vs. physoclisti species), physiological or behavioral (i.e. acclimation depth) similarities. Ecological consequences to fish populations are particularly significant to both long- and short-distance migrators, as their feeding or reproductive processes as well as flood sheltering or wintering behaviors are disrupted.

To address these concerns, so called environmentally-enhanced turbines have been designed [5], particularly targeting low-head sites. Recommendations from Andritz Hydro emphasized variable turbine speed, optimization of operating schemes, reduced gap between hub and runner vanes, minimized turbulence and cavitation, blunt leading edges, and alignment of stay and guide vanes [6]. Within the Advanced Hydropower Turbine System Program launched in 1993, Voith Hydro's Minimum Gap Runner (MGR) Kaplan turbine and Alden Research Laboratory's Francis turbine concepts demonstrated remarkable improvements in survival rates of 38 - 175 mm body length (BL) rainbow trout *Oncorhynchus mykiss*, 102 mm BL coho salmon *O. kisutch*, 249 - 431 mm BL American eel *Anguilla rostrata* and 87 mm BL alewife *Alosa pseudoharengus* [7–9]. The hydrokinetic turbine produced by Hydro Green Energy, the first surface-suspended, asymmetrically-ducted horizontal axis turbine to be installed in the U.S.A., resulted in recapture rates averaging 98 % and negligible impacts on 115–235 mm and 388–710 mm BL of several fish species [10]. Recent innovations, including the Very Low Head (VLH) Kaplan turbine, Archimedes screw and Natel Energy's Restoration Hydro Francis Turbines yielded low injury and mortality rates across diverse fish species and size classes [11–16].

Increased share of renewable energy sources of intermittent nature such as solar and wind requires compensatory measures for the fluctuations to maintain grid stability: energy storage systems are an effective solution for this problem [17]. Pumped Hydro Energy Storage (PHES) is a mature technology with many advantages such as long lifetime and high energy capacity, but the conventional technology is developed for sites with high head. To make it more suitable for low head areas, a high performing low-head pumped hydro energy storage (LH-PHES) technology is to be developed. A reversible pump-turbine (RPT) is ideal for pumping the water by consuming excess power and generating the required power by turbinizing in a PHES plant. The traditional high head operation requires a Francis turbine type configuration while the low head operation with high flow rate requires an axial machine type such as a Kaplan or propeller turbine due to high specific speed. While a Kaplan type RPT can yield very high performances in turbine mode, their pump mode efficiencies are not great [18], the main reason being the compromised design of guide vanes to cater to flow in both directions for operating as a pump and a turbine [19]. A contra-rotating turbine concept is studied in many areas of power generation such as wind and tidal and their superior efficiency in tidal power applications is proven. A contra-rotating axial pump and turbine offer many advantages over conventional single rotor setups such as better efficiency and cavitation performance, wider operating ranges and a more compact size [20]. Besides these advantages, a variable speed operation of the rotors can offer additional benefits: it helps improving efficiency and stability, eliminating cavitation and thus extending the life of hydropower units. In addition, a faster transition between pump and turbine mode can be achieved [21]. Due to all these benefits, a shaft-driven variable-speed contra-rotating propeller reversible pump turbine (SDCRRPT) was designed and its fish friendliness aspect analyzed and

presented in this study.

This research modeled the hydraulic stressors and biological impacts generated by both an initial design and a scaled version of the optimized design of a shaft-driven variable-speed contra-rotating propeller reversible pump turbine (SDCRRPT) in terms of mortality and mortal injury for two model fish species, namely Atlantic salmon *Salmo salar* and European eel *Anguilla anguilla*, building upon the groundwork established within the EU H2020 project ALPHEUS (Augmenting grid stability through Low-head Pumped Hydro Energy Utilization & Storage). By providing a deeper understanding of the stressors leading to fish injury and mortality, the overarching aim of the study was to aid in improving the design and operation of hydropower units to reduce ecological impacts as well as suggest possible countermeasures that may be taken to protect aquatic environments.

2. Methods

2.1. Design of contra-rotating turbines

The ALPHEUS project investigated three promising Reversible Pump Turbine (RPT) technologies for a low to ultra-low head (i.e. 1 - 20 m) operating conditions, namely Shaft-Driven variable-speed Contra-Rotating propeller RPT (SDCRRPT), Rim-Driven variable-speed Contra-Rotating propeller RPT (RDCRRPT) and Positive displacement RPT.

Many advantages of a contra-rotating RPT are introduced in the previous section and this justifies the choice of SDCRRPT. RDCRRPT is similar to the shaft-driven concept with the main difference being the integration of motor/generator at the periphery of the rotor rather than at the shaft region. This helps avoiding the necessity of a large bulb structure housing electrical machines at the hub of the rotor, potentially reducing the hydraulic losses to it associated. Rim-driven marine propulsors are a highly researched field and studies on rim driven turbines are also available [22]. Rim-driven marine propulsors offer many advantages over shaft driven counterpart such as compact design, higher motor and hydraulic efficiency and reduced demand for lubrication and cooling systems [23], hence this configuration was also considered. Positive displacement RPT due to its lower specific speed could be a good fish-friendly technology and a lobe type configuration seems to handle fish and solid without extra mitigation measures [24]. This along with other advantages makes this configuration a worthwhile choice for this application. Details on the general characteristics and key features of the prototypes, machines performance characteristics, assessment of prototype performance impact on LH-PHES cost and operation simulation and optimization model are provided in [17].

The TURBOdesign Suite from Advanced Design Technology¹ was used to develop an initial design of a SDCRRPT at prototype scale. This software generates the blade geometry of both the rotors based on an inverse design approach where blade loading (essentially, normalized static pressure distribution) is specified as an input and the 3D blade geometry is produced as the output. With this method the designer has a direct control over the flow field and high performing designs can be obtained quickly [25]. The rotor design was performed in pump mode and analyzed using Computational Fluid Dynamics (CFD) simulations in both pump and turbine modes. The chosen design point specifications included a head of 9 m, flow rate of 130 m³ s⁻¹, rotor 1 rotational speed of 50 rev min⁻¹ and a rotor 2:rotor 1 speed ratio of 0.9. The aim was a target power output of 10 MW in turbine mode at a head of around 9 m. A meanline design of the machine using TURBOdesign Pre software based on the above specifications suggested a machine diameter of 6.06 m with blade numbers of 8 and 7 for rotor 1 and rotor 2 respectively. The meridional geometry, work coefficient blade number, thickness distribution and an appropriate blade loading was input in TURBOdesign 1

¹ <http://www.adtechnology.com/products>

software to generate the blade design for each rotor. The initial design obtained was named as "Prototype 0". The CFD analysis of the initial design showed that a power of 10 MW was achieved in turbine mode at a flow rate of $143 \text{ m}^3 \text{ s}^{-1}$ and a head of 7.8 m with more than 91 % efficiency.

A multi-objective optimization was then performed to improve the hydraulic performance of the SDCRRPT [26]. The optimization process was based on a Design of Experiments (DoE) and Response Surface surrogate model approach [27]. The optimization was carried out using NSGA-II (Non-dominated Sorting Genetic Algorithm II) algorithm [28]. Twenty-one design parameters covering a wide range of geometry variations were screened in a sensitivity DoE study: they included 8 meridional geometry parameters, 10 blade loading parameters, 2 blade stacking parameters and the speed ratio between rotors. A sensitivity study involving 36 designs with variation of all the mentioned parameters was conducted to identify the 11 most influential design parameters. Then a DoE matrix consisting of ~100 designs with the variation of influential design parameters was generated for an optimization. All the designs were analyzed using CFD in both operating modes at 3 different operating points. The optimization objective was to maximize power in turbine mode and minimize power in pump mode head constrained in the required range. Dassault Systèmes Isight software was used for generating the surrogate model and optimization, and the best performing optimization solution was named "Prototype 1" (Fig. 1, Table 1). Due to optimization the Prototype 1 design has become more compact with smaller tip and hub diameters and the rotational speed at design point in pump mode is higher. Both Prototype 0 and Prototype 1 were then evaluated for fish mortality.

2.2. CFD modelling

Computational Fluid Dynamics (CFD) simulations for the fish friendliness analysis was performed using Siemens Star CCM+ software. The full wheel passage of the contra-rotating RPT with a straight hub was only modelled in CFD simulation. The CFD domain consisted of two stationary domains S1 and S2 and two rotating domains R1 and R2 (Fig. 2).

Appropriate stressors were extracted from CFD simulations. They included scalar stressors such as nadir pressure, maximum strain, and maximum TKE (Turbulence Kinetic Energy) as well as the collision data. These were calculated for representative fish trajectories using particle tracking functionality in the CFD software. Individual particles were modelled by injecting them from specific seeding locations and tracking within the flow field till the exit boundary. This data was extracted for each particle modelled along with the particle ID for each configuration of the turbine simulated, and served as input for the Biological Performance Assessment (BioPA v3.0) software developed by Pacific Northwest National Laboratory (USA).

The Lagrangian multiphase unsteady RANS CFD analysis with multiple reference frame (MRF) approach was used instead of DEM (Discrete Element Method) as the former is relatively less computationally intensive. This approach models a centre of mass collision of the

Table 1

Comparison of the main design parameters between the initial and optimized prototypes.

Design Details	Prototype 0	Prototype 1
Rotor 1 speed [rev min ⁻¹] @ design point	50	60.9
Speed ratio @ design point	0.9	0.75
Shroud diameter [mm]	6064	5680
Hub to shroud diameter ratio	0.58	0.45
Rotor 1 blade number	8	8
Rotor 2 blade number	7	7

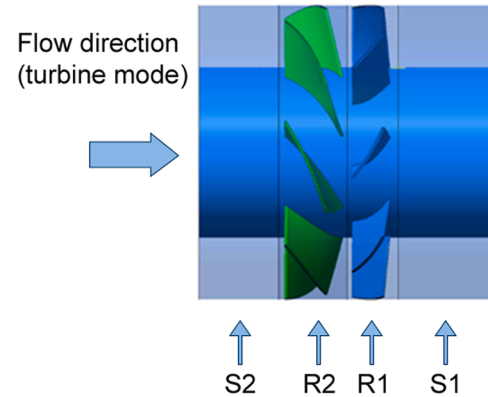


Fig. 2. SDCRRPT CFD analysis domain.

particles with the walls and hence surface contact forces are not accurately resolved. Meshing was performed in Star CCM+ with polyhedral elements and prism layers close to the walls, with a total of ~8 million mesh elements, chosen based on a grid independence study.

The k- ω SST turbulence model was used, and a $y^+ < 30$ was ensured on most of the blade surfaces. A timestep of 0.01 s corresponding to less than 3° rotation of the blade was chosen. Velocity at the inlet, static pressure at the outlet and zero slip on the solid wall were applied as boundary conditions. All the above settings as well as the orientation of the rotors complied with technical documentation by Pacific Northwest National Laboratory [29,30]. A single point CFD solution with 12 s of physical simulated time took ~16 hours to complete.

Initially a steady CFD simulation was conducted to achieve steady state conditions. This solution served as the initial condition for the following unsteady simulation with particle injection. Passive tracer particles were injected from a specified injector plane. Injection locations/cells on the plane were randomly assigned by the software based on a specified point inclusion probability parameter. Fourteen seeds were injected randomly over the inlet plane at a 0.1 s-interval for a total of 10 s, amounting to a total sample size of 1400 seeds. Such seed distribution was chosen following an evidence-based approach [31,32]. Particles were modeled as neutrally buoyant spheres (i.e. with a specific gravity of 1). Particle diameters were calculated based on the fish mass, as per the modeling proposed by Romero-Gomez and Richmond [33]. Particle trajectories (regarded as equivalent to estimated fish trajectories) and collision boundary sampling data were extracted from the CFD model with the Lagrangian particle tracking method by means of custom post-processing Java scripts. Track data was calculated based on the following momentum equation:

$$M_{particle} \frac{dU_{particle}}{dt} = F_d + F_p + F_g + F_{vm}$$

where $M_{particle}$ is the mass of the particle, $U_{particle}$ is the velocity, F_d is the drag force, F_p is the force due to pressure gradients, F_g is the gravity force and F_{vm} is the virtual mass force [33]. The Boundary sampling technique helped obtain data of particle collision with solid boundaries from the simulation. A sample plot record of collision events and particle

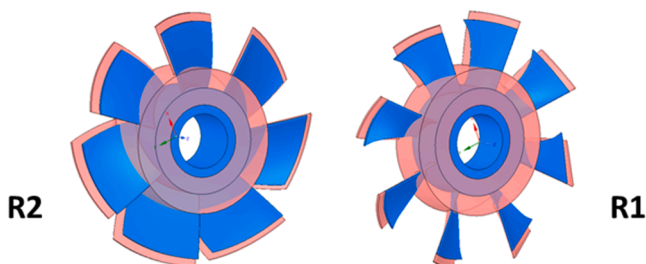


Fig. 1. Prototype 0 (Orange) and Prototype 1 (Blue) designs of shaft-driven variable-speed contra-rotating propeller reversible pump turbine (SDCRRPT).

movement through turbines is shown in Fig. 3A-B. Based on the particle trajectory data and collision data, BioPA v.3 determines a fish friendliness score.

2.3. Biological performance assessment

The Biological Performance Assessment (BioPA) [34], (Battelle IPID 31784, Battelle Memorial Institute, Pacific Northwest National Laboratory, license agreement # 530469, 1-year license from June 23rd, 2021), is a tool developed within the framework of Hydropassage (www.hydropassage.org) to inform safer turbine designs. BioPA enables the comparative assessment of potential impact to fish populations based on CFD models of the hydraulic conditions of turbine designs, which can then be ranked based on the BioPA score, a proxy of fish friendliness.

The BioPA workflow was established using the initial SDCRRPT design, an operating point in the turbine mode with a volume flow rate of $143 \text{ m}^3 \text{ s}^{-1}$ and an output power of 10 MW. The main advantage of BioPA v.3 over v.2.1 is the better prediction of collision events of particles with solid structures of the turbine although volitional collision avoidance behavior of the fish is not captured [33]. Since blade striking is a probable strong hazard for a fish in a contra-rotating turbine, BioPA v.3 was preferred over v.2.1.

The turbine environmental performance assessment was compared between two designs, two operating conditions and two fish species. The two configurations chosen were the initial SDCRRPT design, called Prototype 0, and a scaled version of the optimized design, called Prototype 1. Both designs were CFD-simulated for an operating condition in turbine mode at a full load power output of approximately 10 MW. At such power output, rotors R2 and R1 of Prototype 0 operated at rotational speeds of 45 rev min^{-1} and -50 rev min^{-1} , respectively, at a flow rate of $143 \text{ m}^3 \text{ s}^{-1}$. Rotors R2 and R1 of Prototype 1, instead, operated at a rotational speed of $34.6 \text{ rev min}^{-1}$ - 46 rev min^{-1} , respectively, at $138 \text{ m}^3 \text{ s}^{-1}$ flow rate. An additional simulation was conducted

for the rotors of Prototype 0 at the same operating speeds but at a flow rate of $130 \text{ m}^3 \text{ s}^{-1}$ at a partial load power output of approximately 5 MW (Table 2).

The fish species considered were Atlantic salmon *Salmo salar* of 15 cm BL and European eel *Anguilla anguilla* of 30 cm BL. As per the modelling equation in [33], particle diameters were set at 0.053 m and 0.086 m, respectively.

We specify that BioPA v.3 does not allow for the simultaneous modelling of contrarotating turbine elements, which had to be therefore herein considered individually with the underlying assumption that each rotor independently affects the investigated species because of the spacing between rotors being greater than the largest body length of the fish investigated. Both species were assessed for susceptibility to rapid decompression, shear and collision. Only *S. salar* was analyzed for susceptibility to turbulence as no biological model was available in BioPA v.3 for European eel or its surrogate species. Based on surrogacy, biological response models developed for Chinook or Rainbow trout and American eel were employed for estimating susceptibility of *S. salar* and *A. Anguilla*, respectively. Depth weighting was not applied to either Prototype 0 or 1 for any particle track. Blade thickness of 60 mm was input for collision analysis. The most severe endpoint of mortality was selected for all stressor response models, except for the estimation of the effects of rapid decompression on *S. salar*; in this case, the biological response model predicting the probability of mortal injury (i.e. injuries highly associated with and likely to predict mortality) was used. The probability of adverse passage was calculated by multiplying the probability of exposure (Pe, obtained from the statistics file data for each stressor) by the probability of response (Pm, obtained from distribution data for each stressor at various stressor magnitudes) for the full range of stressor magnitudes based on the chosen response model. A Passage Quality Index (PQI) was then calculated as a function of both the probability of exposure (Pe) and the probability of adverse response at a given exposure (Pm) per contrast (design * stressor * species). PQI ranged from 0 to 500, with lower PQIs corresponding to lower estimates of survival rates (i.e., higher likelihood of injury). A PQI of 500 indicates no adverse effect estimated.

2.4. Experimental model selection justification

Atlantic salmon and European eel were selected as model species of the present desktop study due to their representativeness for distinct biological, ecological and conservation traits as well as extensive data availability within the BioPA toolset and SPOT (Swim Performance Online Tools) [35] (see [36]) tools.

In particular, the Atlantic salmon, classified as benthopelagic, utilizes demersal, mid-water, and surface water column habitats for swimming and feeding purposes, whereas the European eel, being benthic, exhibits strong bottom-dwelling behavior throughout its life stages particularly at the yellow (non-mature adult) and silver (migratory adult) stages.

Both species are migratory, but exhibit opposed migration patterns, i.e. anadromy in the Atlantic salmon vs. catadromy in the European eel. Riverine habitats serve as migration corridors for both, making them pertinent subjects for studying hydropower impacts, laying the basis for

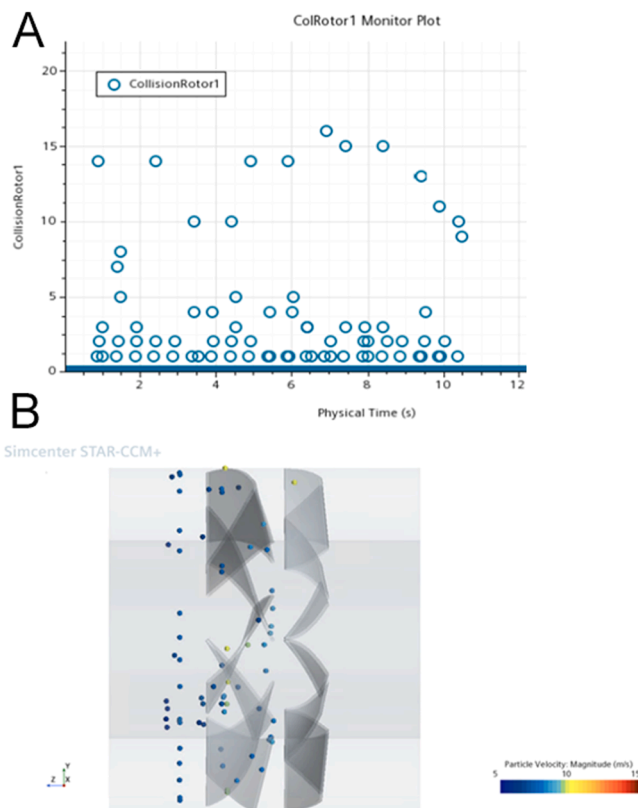


Fig. 3. A: A sample collision plot. B: A sample picture of particle movement through the turbine.

Table 2

Summary of the two SDCRRPT design configurations employed in the BioPA-based fish friendliness analysis.

Prototype	Rotor	Rotational speed (rev min ⁻¹)	Flow rate (m ³ s ⁻¹)	Power output (MW)
P0	R1	-50	143	10
P0	R2	45	143	10
P1	R1	-46	138	10
P1	R2	34.6	138	10
P0	R1	-50	130	5
P0	R2	45	130	5

estimating the extent of impact propagation to marine resources.

Lastly, a high fraction of dose-response equations available in the BioPA tool catalog was generated for fish species belonging to Salmonidae and Anguillidae families such as American and European eel (*A. rostrata*, *A. anguilla*) as well as for Chinook salmon (*O. tshawytscha*), rainbow/steelhead trout (*O. mykiss*) and Atlantic salmon (*S. salar*) (e.g. [16,37–44]). When necessary, family or genus surrogacy was exploited.

3. Results and discussion

BioPA-based fish friendliness performance of SDCRRPT designs was modelled for Atlantic salmon and European eel as follows:

- Contrast 1: Prototype 0 vs Prototype 1 at 10 MW (comparing 2 designs at full load power output);
- Contrast 2: Prototype 0 – 10 MW vs 5 MW (comparing 2 operating conditions – full load vs part load for same design).

While seed sample size varied greatly across studies modelling fish sensitivity to simulated flow (e.g. [32,34]), seed sensitivity analyses demonstrated a certain extent of variability in the resulting BioPA score, and this aspect should consequently be approached with caution. Herein, we increased the seed sample size by a factor of 2.3 compared to Singh et al. [32] to ensure better coverage of the flow field and to capture variability in particle trajectories, especially in zones near rotating components and for modeling rare or localized stressor exposures, hence to truthfully characterize hydraulic stressors in low head pumped hydro systems.

Table 3 summarizes the biological response models employed for estimating adverse effects per target species, while Table 4 reports the probability of adverse passage per mechanism per rotor per operating condition for *Anguilla anguilla* and *Salmo salar*.

Rapid decompression, or changes in ambient pressure, causes barotrauma to fish that are not able to adjust to the sudden decrease in pressure prior to returning to near surface pressure in the downstream channel, the extent of which depends on the magnitude and rapidity of pressure reduction, on fish acclimation time to changing pressure conditions, and the acclimation pressure of fish when entering the turbine intake [49]. This stressor emerged as the least impactful stressor across all examined fish species, posing minimal risk of mortal injury or mortality. Both rotor designs in all operating conditions consistently produced high nadir pressure values, resulting in a reduced likelihood of mortality and injury. Fish entering hydropower plants transition from deep to shallow waters and experience rapid pressure changes, especially during turbine passage. Conventional hydropower turbines impose pressures ranging from 460 to 2 kPa [47], with the degree of decompression influenced by turbine design, operating conditions, and

Table 3
Biological response models employed for estimating adverse effects per target species, with indication of the surrogate species for which the models were developed, when appropriate.

Stressor	Adverse effect	Ref.	Species	Surrogate species
Rapid Decompression	Mortal injury	[45]	<i>S. salar</i>	Chinook salmon
	Mortality	[46]	<i>A. anguilla</i>	American eel
Fluid Shear	Mortality	[44]	<i>S. salar</i>	Fall Chinook salmon
	Mortality	[46]	<i>A. anguilla</i>	American eel
Collision	Mortality	[47]	<i>S. salar</i>	Rainbow Trout
	Mortality	Not publicly available	<i>A. anguilla</i>	American eel
Turbulence	Mortality	[48]	<i>S. salar</i>	NA

head of the plant [50,51]. Pressure-related injuries depend on the magnitude and rate of pressure drop, as well as fish acclimation time and initial pressure conditions [52]. While gradual acclimation can prevent harm, hydropower-induced pressure changes are often abrupt [53]. These changes occur in three stages: a pressure increase before the turbine runner, rapid decompression within less than a second during turbine passage, and a return to ambient pressures downstream [54]. Because of these steps, rapid decompression is regarded as the most serious hydropower mechanism of damage to fish biodiversity, as most migratory fish are lethally impacted by sudden swim bladder rupture [5]. The low probabilities of adverse passage may be explained by the fact that elevated nadir pressures herein simulated likely fell above critical thresholds for barotrauma, thus posing minimal risk for eel or salmon passage.

Due to the lack of dose-response models for *Anguilla anguilla* or suitable surrogates, analysis performed only on *Salmo salar* revealed negligible effects of turbulence. Turbulence kinetic energy (TKE), i.e. the mean kinetic energy per unit mass, ranged between 0 and 3 J Kg⁻¹ for both turbine prototypes. According to the mortality response model by [48], this range was associated with a 0 % likelihood of mortality, affirming that turbulence in the observed operating regimes does not substantially impact salmonids survival. Turbulence in hydropower systems arises from small, strong directional changes in water flow [55] or the breakdown of shear zones [39]. It is typically confined to areas past the turbine hub and near draft tube piers, affecting only 2 % of the flow in conventional turbines [56,57]. Small-scale turbulence, found near runner blades, can cause injuries like body compression and disorientation [58], while large-scale turbulence in draft tubes generates vortices that may disorient fish, increasing predation risk [59]. While turbulence is linked to shear stress and remains poorly understood [60], only eddies matching fish size are deemed hazardous [61]. Accordingly, turbulence is not considered a significant injury source for downstream-migrating fish [62].

Shear stress was identified as the most concerning stressor, with pronounced effects depending on species. Shear is a mechanism that is generated when two masses of water moving in different directions or distinct velocities intersect, or where moving water slows near a solid structure, in both cases resulting in friction forces acting on the fish body [61]. The index of the physical force that fish experience when subjected to a shear environment is the strain rate, defined by equation: $S = \frac{\Delta v}{\Delta y}$, where Δv is the change of mean water velocity and Δy is the distance, perpendicular to the force, over which such velocity change occurs. Although shear is a naturally occurring stress mechanism, and fish have evolved several adaptations to counteract it [55], salmon displayed significant vulnerability, with mortality rates in simulated flows ranging from 42.74 % (P0 R2 at partial load power) to 56.32 % (P1 R1 at full-load power). These rates indicate that shear stress exceeded the tolerance limits of the species and thus presents a critical factor in injury/mortality risk during turbine passage. Worthy of note, the probabilities of adverse passage were comparable among rotor pairs of the initial SDCRRPT design operating at full load vs partial load (contrast 2): a possible explanation is that hub-to-tip and speed ratios (i.e. the most influential parameters determining shear, as per a sensitivity study) were constant in the two operating conditions. In contrast, *A. anguilla* exhibited negligible susceptibility to shear, similarly to what already observed during laboratory experiments on American eel [46]; such resilience underscores the importance of tailoring hydropower designs to account for diverse biological tolerances. Shear stress arises when water masses with differing velocities or directions intersect or when moving water slows near solid structures, generating friction on fish bodies [61]. While natural shear in the wild is minimal (~100 N/m²) and rarely harmful to fish [63,64], hydropower plants can produce shear levels of 500–5000 N/m² [65]. These forces are most pronounced near turbine blades, spillways, and draft tube boundaries, with extreme conditions at blade tips and hubs [59]. Turnpenny et al. [66], by

Table 4Probability of adverse passage for *anguilla* and *Salmo salar*, per mechanism per rotor per operating condition.

Species	Mechanism	P0 R1, 10 MW	P0 R2, 10 MW	P1 R1, 10 MW	P1 R2, 10 MW	P0 R1, 5 MW	P0 R2, 5MW
<i>A. anguilla</i>	Rapid decompression	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
	Fluid shear	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
	Collision	4.73 %	3.04 %	8.34 %	0.00 %	5.71 %	0.00 %
<i>S. salar</i>	Rapid decompression	0.10 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
	Fluid shear	47.01 %	42.82 %	56.32 %	35.69 %	49.97 %	42.74 %
	Collision	8.13 %	4.93 %	15.54 %	0.12 %	19.39 %	0.00 %
	Turbulence	0.01 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %

applying CFD simulations to identify the risk of injury from shear effects in small low-head (< 30 m) Francis and Kaplan turbines, revealed that shear was of minor importance in both turbine types based on the low occurrence probabilities. Due to the difficulty in truthfully recreating shear under controlled conditions, its actual effects on downstream passing fish are not well understood, and the development of dose-response equations was hindered. Nevertheless, from studies conducted under controlled conditions employing water jets, injuries such as scale losses, hemorrhaging, and eye, skin and skeletal damages, as well as mortality were reported as a consequence of shear [54]. Most importantly to what was herein observed, the authors highlighted species-specific sensitivity differences to shear (i.e. salmon of 85 mm BL did not suffer any minor or major injuries at strain rates of 517 and 688 s⁻¹, respectively, while American shad *Alosa sapidissima* was already susceptible at rates of 341 s⁻¹).

Collision impacts were found to vary widely based on species, rotor design, and operating conditions. Collisions with physical structures of the hydropower plant, either fixed (e.g. stay or guide vanes) or moveable (e.g. turbine blades), are the predominant source of injury and death in fish [67] and result in abrasion, grinding and striking of organisms. For salmon, collision risks were notably higher for R1 than R2. At full-load power, adverse passage probabilities for R1 ranged from 8.13 % (P0) to 15.54 % (P1), whereas R2 consistently demonstrated better performance (4.93 % for P0). At partial load conditions, collision probabilities increased further for R1, reaching 19.39 %, highlighting how the same rotational speed at reduced flow rates might elevate the probability of collision for salmonids. This may be explained by the higher relative blade speed versus water velocity occurring in this scenario, that ultimately causes an increased exposure time of fish to rotating blades and hence a higher probability of encountering a blade. Conversely, eel collision probabilities were significantly lower across all scenarios. At full load, collision risks ranged from 3.04 % to 8.34 %—approximately half of that observed for salmon. At 5 MW, R1 remained slightly more impactful for eel (5.71 %) than R2 (0 %). By assessing R1 biological performance across operating condition, collision appeared slightly more impactful at partial load power. These differences suggest that eels, and anguilliformes in general, are less sensitive to rotor-induced collision stress than salmon, with reduced exposure across operating conditions. The risk and severity of fish injuries or mortality from turbine blade strikes depend on turbine type, blade characteristics, fish-blade interaction, and biological factors. Francis turbines, with smaller inter-blades spaces and higher velocities, cause higher mortality (5–50 %) compared to Kaplan turbines (5–15 %) and Archimedes screws, which are the most fish-friendly due to low blade speed and the presence of fewer blades [68,69]. Blade thickness, velocity, and shape critically influence injury risk, with thinner, faster blades causing severe damage, while thicker, slower blades reduce mortality [39,70]. Strike outcomes vary by impact location, angle, and fish morphology, with mid-body and head impacts at steep angles being most lethal [16,51]. Some species were demonstrated to be inherently less sensitive than others. For instance, Saylor et al. [37] observed low mortality rates of American eel *A. rostrata* at the highest velocity tested (13.6 m s⁻¹), while *A. anguilla*, a closely related species, did not experience mortality until velocity of > 8 m s⁻¹ [71], suggesting that anguillids are more resistant to blade strike impact. Variations in species sensitivity highlight the need

for species-specific assessments to mitigate turbine-related impacts effectively.

Notably, Rotor 1 of the optimized design (P1) consistently demonstrated higher adverse passage probabilities compared to its counterpart in the initial SDCRRPT design (P0), increasing collision-related risks by approximately 1.76-fold for salmon and 1.91-fold for eel. These results highlight the need for further refinements in P1's rotor configuration to enhance fish-friendliness. The species- and configuration-specific risk profiles also highlight the need for adaptive strategies in turbine design to balance power generation with ecological conservation of aquatic communities.

The Passage Quality Index (PQI) scores further illustrated the interplay of stressors, rotor design, and operating conditions (Fig. 4).

For *A. anguilla*, PQIs for decompression and shear stressors were consistently the maximum (500), indicating minimal risk. Collision PQIs, however, varied, reinforcing R2's superiority, that is R2 may be inherently less hazardous for fish than R1 as it was consistently modelled to exhibit higher PQI values compared to R1 within the same operating condition, i.e. 485 vs. 478 for P0 at full load power, 500 vs. 458 for P1 at full load power, and 500 vs. 471 for P0 at partial load power. These results reaffirm the eel's resilience to most stressors, with collision emerging as the primary area for optimization. For *S. salar*, PQIs were highest for decompression and turbulence but showed marked variability for shear and collision. For Prototype 0 rotors, PQIs of shear exposure were comparable across both full-load and partial load power outputs (i.e. 265 vs. 286, and 250 vs. 286, respectively). However, the difference between PQI values resulting from R1 and R2 simulations of P1 was much more pronounced (i.e. 218 vs. 322). A significant variability was also evident in PQI values related to collisions. The collision PQI of R2 ranged from 475 at 10 MW for P0 to 500 for both P1 at 10 MW and P0 at 5 MW; in contrast, the lowest R1 PQIs were found for P1 at 10 MW (422) and for P0 at 5 MW (403).

In general, rotor 2 was identified as the more suitable choice for increasing fish passage safety due to the simulated mitigation of stressors in hydropower systems. The substantial variability in shear and collision PQIs, particularly for rotor 1, highlights that both operational adjustments and rotor configuration can markedly affect biological outcomes, underlining the importance of careful design considerations to enhance fish-friendliness in hydropower operations. Worthy of note, the use of particle tracking as proxy for fish trajectories in CFD modelling cannot capture volitional avoidance behavior of fish during turbine passage. It is important to emphasize that these limitations are not unique to the present study, but are intrinsic to the CFD–BioPA framework itself, which has nevertheless become a widely adopted tool for biological performance assessment of hydropower turbines. While the method has been validated with respect to hydrodynamic accuracy and predictive capability using species-specific dose-response models derived from controlled laboratory studies, it does and cannot possibly incorporate fish behavioral traits such as volitional avoidance, orientation, or learning. For these reasons, re-optimization of the turbine designs within this framework would not yield meaningful improvements given the conservative nature of the underlying assumptions. The lack of behavior modeling is a known shortcoming shared across all implementations of the approach, and may lead to conservative -i.e., potentially overestimated- predictions of fish injury or mortality, particularly

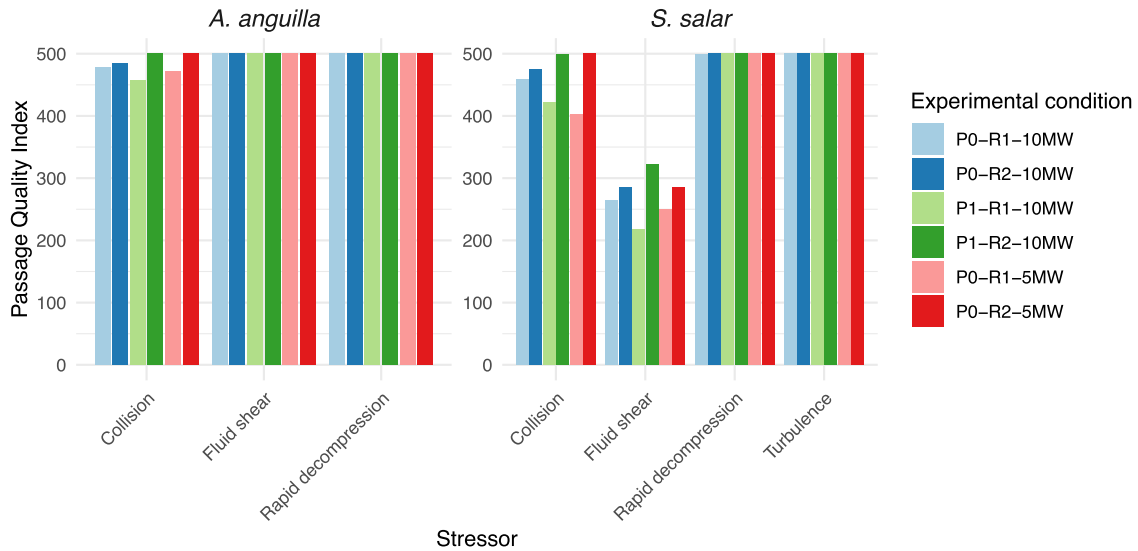


Fig. 4. Passage Quality Indices per species, per stressor per experimental setting.

for species capable of evasive responses during turbine passage. As such, the results should be interpreted as upper-bound estimates of biological risk, rather than definitive real-world outcomes. Nevertheless, based on the resulting expected species-specific impact at prototype scale of the optimized SDCRRPT, the employment of either physical, mechanical or sensory behavioral barriers [72] combined with bypass systems is warranted.

Due to the possible uncertainty as to how exposure to multiple stressors in a hydropower facility may affect fish susceptibility, a synthetic PQI score per target species, operating condition and rotor was calculated by applying an equal weight to each stressor. This represents an overall performance score for fish passage safety evaluation enabling comparisons between different operating conditions or designs in hydropower plants.

The cumulative PQI scores for both salmon and eel (Fig. 5) reflected similar patterns to those of individual damage mechanisms both within and between operating conditions and contrasts tested.

Specifically, rotor R2 in the scaled-up version of the SDCRRPT optimized prototype design achieved the highest fish-friendliness scores at a full power output. This performance indicates that the design modifications resulting in Prototype 1, particularly at this higher load, were indeed efficacious for contributing to safer passage conditions for fish. Interestingly, similar high PQI values were observed for R2 in the

original SDCRRPT design when operating at a reduced, partial load power output of 5 MW. Both lower power levels and optimized design are suggested to contribute positively to fish passage quality, although the optimized design at higher loads still offers the best performance.

The difference in fish-friendliness between rotors was particularly noticeable for salmon, which appeared more sensitive to variations in rotor design and operating conditions than eel. For example, in the P1 configuration at 10 MW, PQI scores for salmon ranged from 413 to 447, whereas for P0 at 5 MW they ranged from 410 to 455. These scores indicate a substantial improvement in safety for salmon when rotor R2 is used, especially in the P1 prototype at higher power output.

As for eel, PQI scores remained consistently high, regardless of rotor type, power output, or prototype design. Eel PQI values across all conditions ranged from 486 to 500, reflecting a high resilience to the potential stressors simulated here. A similar lack of acute response was seen in terms of neuroendocrinological stress when the species was exposed to 30-min varying entrainment flow speeds, carefully chosen based on available swimming fatigue curves, near pump inlet fish screens [36]. This consistency suggests that eel may be less affected by rotor design and operational changes, as well as by diversion structures, perhaps due to their distinct body structure or behavior when passing through hydropower turbines.

Overall, the findings underscore the benefits of design optimization in promoting fish-friendly hydropower systems, particularly for species like salmon that are more vulnerable to stressors. We highlight that, although previous numerical modeling studies have assessed the relative biological performances of turbine runner designs, specifically Kaplan units, both for practical applications or evaluation of surrogacy applicability [29,31,32,34,43,73,74]), this work is, to the best of our knowledge, the first to assess the biological impacts of hydraulic stressors generated by CRPPT turbines designed for low head hydropower purposes.

4. Conclusions

Two prototypes of a Shaft-Driven variable-speed Contra-Rotating propeller Reversible Pump Turbine (SDCRRPT) were evaluated for their impact on two target species, *Anguilla anguilla* (30 cm simulated body length) and *Salmo salar* (15 cm simulated body length). The two layouts, initial design (prototype 0) and optimized design (prototype 1), were simulated at full or partial load power output both comparatively and within design. Rapid decompression was found to be the least impacting stressor on both species in all simulated runs. Both prototypes

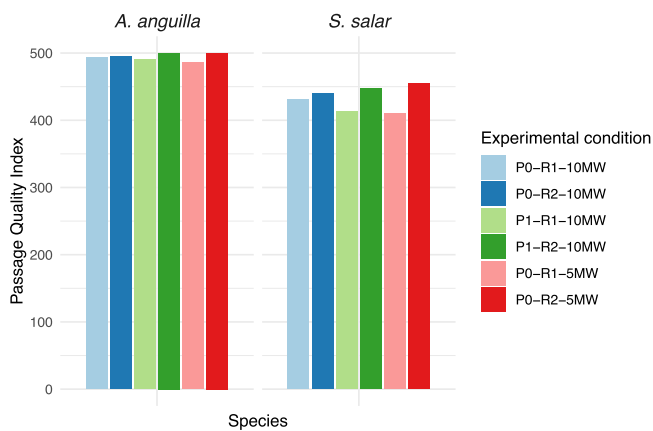


Fig. 5. Cumulative passage quality index per species per experimental setting. Each stressor was given an equal percentage weight in calculating the cumulative PQI.

were associated to high values of nadir pressure, which was related to minimum risk of mortality and injuries (i.e. PQI of 500). Shear and turbulence were also found to have the lowest impact on eel and salmon, respectively, in all simulations. Eel of 30 cm BL were slightly impacted by collision, especially by the scaled version of the optimized design at full load. Fluid shear was the most concerning stressor for 15-cm BL salmon, with prototype 1 at 34.6 rev min⁻¹ and full load being the most impactful. Such configuration did not produce any collision risk, even though collision is generally the second most severe injury mechanisms for this species in hydropower systems. For these reasons, the cumulative PQI shown at Fig. 5 reported a higher susceptibility for salmon than eel.

The holistic approach allowed by CFD computations and BioPA modeling demonstrated the persistence of shear and collision impacts, implying that fish mortality and injuries cannot be avoided during downstream passage through Pumped Hydroelectric Energy Storage infrastructures, warranting the employment of physical, mechanical or sensory behavioral barriers combined with bypass systems. These results emphasize the importance of adaptive, species-informed strategies in hydropower design to balance ecological conservation with energy production. In view of the expected fish mortality at prototype scale of the optimized SDCRRPT, the use of fish screens is strongly recommended for preventing mortality of adult specimens.

CRedit authorship contribution statement

A Miccoli: Conceptualization, Project administration, Data curation, Visualization, Writing – original draft. **A De Luca:** Formal analysis, Investigation, Writing – review & editing. **M Marcelli:** Supervision, Writing – review & editing. **M Joseph:** Methodology, Software, Formal analysis, Writing – review & editing. **M Zangeneh:** Resources, Writing – review & editing. **J Bricker:** Project administration, Funding acquisition, Writing – review & editing. **M Peviani:** Supervision, Writing – review & editing. **G Scapigliati:** Conceptualization, Supervision, Writing – original draft.

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.

Acknowledgements

The ALPHEUS project (www.alpheus-h2020.eu) has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement #883553.

References

- [1] IEA. Tracking clean energy Progress 2023. 2023.
- [2] ICES, Joint EIFAAC/ICES Working Group on Eels (WGEEL), ICES Scientif. Reports. (2019).
- [3] European Commission. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). 2008.
- [4] A. Filleul, S. Lavoué, Basal teleosts and the question of elopomorph monophyly. Morphological and molecular approaches, *Comptes Rendus l'Acad. Des. Sci. - Ser III* 324 (2001) 393–399, [https://doi.org/10.1016/S0764-4469\(00\)01302-0](https://doi.org/10.1016/S0764-4469(00)01302-0).
- [5] E. Quaranta, J.I. Pérez-Díaz, P. Romero-Gomez, A. Pistocchi, Environmentally enhanced turbines for hydropower plants: current technology and future perspective, *Front Energy Res.* 9 (2021) 1–6, <https://doi.org/10.3389/fenrg.2021.703106>.
- [6] A. Rammler, Fish Friendly Designs by Andritz Hydro, *Hydro News*. (2017).
- [7] Odeh M. A summary of environmentally friendly turbine design concepts. 1999.
- [8] Cada GF, Amaral S. Determining the best methods for reducing fish mortality. 2011.
- [9] N.M. Nielson, R.S. Brown, ZD. Deng, Review of existing knowledge of the effectiveness and economics of fish-friendly turbines, Session II, Item 2 (2015). Vientiane, Laos PDR: Phnom Penh, Mekong River Commission. Technical Paper No. 57.
- [10] Associates N, An estimation of survival and injury of fish passed through the Hydro Green Energy hydrokinetic system, and a characterization of fish entrainment potential at the Mississippi lock and Dam no. 2 hydroelectric project (P-4306) Hastings, Minnesota, Project (2009).
- [11] S. Bozhinova, V. Hecht, D. Kisliakov, G. Muller, S. Schneider, Hydropower converters with head differences below 2.5m, *Proc Inst. Civ. Eng. Energy* 166 (2013) 107–119, <https://doi.org/10.1680/ener.11.00037>.
- [12] A.T. Piper, P.J. Rosewarne, R.M. Wright, P.S. Kemp, The impact of an Archimedes screw hydropower turbine on fish migration in a lowland river, *Ecol. Eng.* 118 (2018) 31–42, <https://doi.org/10.1016/j.ecoleng.2018.04.009>.
- [13] F. Consulting, Fish Monitoring and Live Fish trials. Ritz Atro Archimedes Screw Turbine, River Dart. Phase 1 report: Live Fish trials, smolts, Leading Edge assessment, Disorientation study, Outflow Monitoring, Prepared for Mann Power Consulting Ltd., York, U.K., 2007.
- [14] F. Consulting, Archimedes Screw Turbine Fisheries assessment. Phase II: Eels and Kelts, Prepared for Mann Power Consulting, York, U.K., 2008.
- [15] S.V. Amaral, B.S. Coleman, J.L. Rackovan, K. Withers, B. Mater, Survival of fish passing downstream at a small hydropower facility, *Mar. Freshw. Res.* (2018), <https://doi.org/10.1071/MF18123>.
- [16] S.V. Amaral, S.M. Watson, A.D. Schneider, J. Rackovan, A. Baumgartner, Improving survival: injury and mortality of fish struck by blades with slanted, blunt leading edges, *J. Ecohydraul.* 5 (2020) 175–183, <https://doi.org/10.1080/24705357.2020.1768166>.
- [17] E.B. Prasasti, M. Joseph, X. Miao, M. Zangeneh, K. Terheiden, Design of shaft- and rim-driven contra-rotating reversible pump-turbine to optimize novel low-head pumped hydro energy storages, *Energy* 306 (2024) 132237, <https://doi.org/10.1016/j.energy.2024.132237>.
- [18] R. Ansorena Ruiz, L.H. de Vilder, E.B. Prasasti, M. Aouad, A. De Luca, B. Geissler, et al., Low-head pumped hydro storage: A review on civil structure designs, legal and environmental aspects to make its realization feasible in seawater, *Renew. Sustain. Energy Rev.* 160 (2022) 112281, <https://doi.org/10.1016/j.rser.2022.112281>.
- [19] W. Xiuli, L. Bin, L. Yang, Z. Yan, Z. Rongsheng, L. Yun, et al., Hydraulic optimization of two-way counter-rotating axial flow pump turbine, *Front Energy Res.* 8 (2020), <https://doi.org/10.3389/fenrg.2020.577232>.
- [20] T. Kanemoto, S. Oba, Proposition of unique pumping system with counter-rotating mechanism, *Int. J. Rotat. Mach.* 10 (2004) 233–240, <https://doi.org/10.1155/s1023621x04000259>.
- [21] I. Kougias, G. Aggidis, F. Avellan, S. Deniz, U. Lundin, A. Moro, et al., Analysis of emerging technologies in the hydropower sector, *Renew. Sustain. Energy Rev.* 113 (2019) 109257, <https://doi.org/10.1016/j.rser.2019.109257>.
- [22] L. Drouen, J.F. Charpentier, E. Semail, S. Clenet, A Global Approach For the Design of a Rim-Driven marine Turbine Generator For Sail Boat, *IEEE*, 2012, pp. 549–555, <https://doi.org/10.1109/ICELMach.2012.6349923>, 2012 XXth Int. Conf. Electr. Mach.
- [23] X. Yan, X. Liang, W. Ouyang, Z. Liu, B. Liu, J. Lan, A review of progress and applications of ship shaft-less rim-driven thrusters, *Ocean Eng.* 144 (2017) 142–156, <https://doi.org/10.1016/j.oceaneng.2017.08.045>.
- [24] J.P. Hoffstaedt, D.P.K. Truijen, J. Fahlbeck, L.H.A. Gans, M. Qudaih, A.J. Laguna, et al., Low-head pumped hydro storage: A review of applicable technologies for design, grid integration, control and modelling, *Renew Sustain. Energy Rev.* 158 (2022) 112119, <https://doi.org/10.1016/j.rser.2022.112119>.
- [25] M. Zangeneh, A compressible three-dimensional design method for radial and mixed flow turbomachinery blades, *Int. J. Numer Meth. Fluids* 13 (1991) 599–624, <https://doi.org/10.1002/flid.1650130505>.
- [26] E.B. Prasasti, M. Aouad, M. Joseph, M. Zangeneh, K. Terheiden, Optimization of pumped hydro energy storage design and operation for offshore low-head application and grid stabilization, *Renew. Sustain. Energy Rev.* 191 (2024) 114122, <https://doi.org/10.1016/j.rser.2023.114122>.
- [27] D. Bonaiuti, M. Zangeneh, On the coupling of inverse design and optimization techniques for the multiobjective, multipoint design of turbomachinery blades, *J. Turbomach.* 131 (2009), <https://doi.org/10.1115/1.2950065>.
- [28] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, *IEEE Trans. Evol. Comput.* 6 (2002) 182–197, <https://doi.org/10.1109/4235.996017>.
- [29] Singh RK, Richmond MC, Romero-Gomez P, Rakowski CL, Serkowski JA. Validation of computational fluid dynamics simulations for the biological performance assessment of hydropower generation units. 2021.
- [30] Singh RK, Plugraht BD, DeSomer K. Biological performance assessment (BioPA) toolset for high head passage 2021.
- [31] M.C. Richmond, J.A. Serkowski, C. Rakowski, B. Strickler, M. Weisbeck, Computational tools to assess turbine biological performance, *Hydro Rev.* 33 (2014) 88–98.
- [32] R.K. Singh, P. Romero-Gomez, A.H. Colotelo, W.A. Perkins, Richmond MC, Computational studies of hydraulic stressors for biological performance assessment in a hydropower plant with Kaplan turbine, *Renew. Energy.* 199 (2022) 768–781, <https://doi.org/10.1016/j.renene.2022.09.016>.
- [33] P. Romero-Gomez, Richmond MC, Simulating blade-strike on fish passing through marine hydrokinetic turbines, *Renew. Energy.* 71 (2014) 401–413, <https://doi.org/10.1016/j.renene.2014.05.051>.
- [34] M.C. Richmond, J.A. Serkowski, L.L. Ebner, M. Sick, R.S. Brown, T.J. Carlson, Quantifying barotrauma risk to juvenile fish during hydro-turbine passage, *Fish Res.* 154 (2014) 152–164, <https://doi.org/10.1016/j.fishres.2014.01.007>.
- [35] Katopodis C, Gervais R. Fish swimming performance database and analyses. 2016.

- [36] A. Miccoli, Luca A De, J. Bricker, F.T. Vriese, R. Moll, G. Scapigliati, Stress response to entrainment flow speed near pump inlet fish screens in two model teleost species, *Anguilla anguilla* and *oncorhynchus mykiss*, *Fishes* 8 (2023), <https://doi.org/10.3390/fishes8030139>.
- [37] R. Saylor, A. Fortner, M. Bevelhimer, Quantifying mortality and injury susceptibility for two morphologically disparate fishes exposed to simulated turbine blade strike, *Hydrobiologia* 842 (2019) 55–75, <https://doi.org/10.1007/s10750-019-04026-x>.
- [38] B.D. Pflugrath, R. Harnish, B. Rhode, B. Beirao, K. Engbrecht, J.R. Stephenson, et al., American eel state of buoyancy and barotrauma susceptibility associated with hydroturbine passage, *Knowl. Manag. Aquat. Ecosyst.* (2019) 20, <https://doi.org/10.1051/kmae/2019012>.
- [39] A.W.H. Turnpenny, M.H. Davis, J.M. Fleming, J.K. Davies, *Experimental Studies Relating to the Passage of Fish and Shrimps Through Tidal Power Turbines, Marine and freshwater biology unit, National Power, Fawley, Southampton, Hampshire, England, 1992.*
- [40] EPRI. Evaluation of the effects of turbine blade leading edge design on fish survival. 2008.
- [41] EPRI, 2010 Tests Examining Survival of Fish Struck By Turbine Blades, Alden Research Laboratory Inc., Palo Alto, CA, USA, 2011. Electric Power Research Institute. Report No.: 1024684. Prepared by.
- [42] R. Saylor, D. Sterling, M. Bevelhimer, B. Pracheil, Within and among fish species differences in simulated turbine blade strike mortality: limits on the use of surrogacy for untested species, *Water* 12 (2020) 701, <https://doi.org/10.3390/w12030701>.
- [43] B. Beirão, B. Pflugrath, R.A. Harnish, S.F. Harding, M.C. Richmond, A.H. Colotelo, Empirical investigation into the applicability of surrogacy for juvenile salmonids (*Oncorhynchus* spp.) exposed to hydropower induced rapid decompression, *Ecol. Indic.* 121 (2021), <https://doi.org/10.1016/j.ecolind.2020.107090>.
- [44] D.A. Neitzel, D.D. Dauble, G.F. Cada, M.C. Richmond, G.R. Guensch, R.P. Mueller, et al., Survival estimates for juvenile fish subjected to a laboratory-generated shear environment, *Trans. Am. Fish Soc.* 133 (2004) 447–454, <https://doi.org/10.1577/02-021>.
- [45] R.S. Brown, T.J. Carlson, A.J. Gingerich, J.R. Stephenson, B.D. Pflugrath, A. E. Welch, et al., Quantifying mortal injury of juvenile Chinook salmon exposed to simulated hydro-turbine passage, *Trans. Am. Fish Soc.* 141 (2012) 147–157, <https://doi.org/10.1080/00028487.2011.650274>.
- [46] B.D. Pflugrath, R.P. Mueller, K. Engbrecht, A.H. Colotelo, American eel resilience to simulated fluid shear associated with passage through hydroelectric turbines, *Knowl. Manag. Aquat. Ecosyst.* (2021), <https://doi.org/10.1051/kmae/2021017>, 2020-Janua.
- [47] S. Amaral, G. Hecker, N. Pioppi, *Fish Passage Through turbines: Application of Conventional Hydropower Data to Hydrokinetic Technologies*, Electric Power Research Institute (EPRI), 2011. Tech. Rep. 1024638. Report by.
- [48] M. Odeh, J.F. Noreika, A. Haro, A. Maynard, T. Castro-Santos, G.F. Cada, Evaluation of the effects of turbulence on the behavior of migratory fish. Prepared for: U.S. Department Energy Bonneville Power Administrat. Div. Fish Wildlife (2002). Project Number 2000-057-00, Contract Number 00000022.
- [49] S. Amaral, T. Castro-Santos, D. Giza, A. Haro, G. Hecker, B. McMahon, et al., *Environmental Effects of Hydrokinetic Turbines On Fish: Desktop and Laboratory Flume Studies*, Electric Power Research Institute (EPRI), 2012. Report by.
- [50] T.J. Carlson, J.P. Duncan, Z. Deng, Data Overview for Sensor Fish Samples Acquired At Ice Harbor, John Day, and Bonneville II Dams in 2005, 2006, and 2007, PNNL 17398, Pacific Northwest National Laboratory, Richland, WA, 2008.
- [51] B.D. Pflugrath, R.K. Saylor, K. Engbrecht, R.P. Mueller, J.R. Stephenson, M. Bevelhimer, et al., Biological response models, Predict. Injury Mortal. Fish Dur. Downstream. Passage Through Hydropower Faciliti (2021).
- [52] P. Jacobson, S. Amaral, T. Castro-Santos, D. Giza, A. Haro, G. Hecker, et al., *Environmental Effects of Hydrokinetic Turbines On Fish: Desktop and Laboratory Flume Studies*, Electric Power Research Institute (EPRI), 2012, <https://doi.org/10.2172/1084623>. Report by.
- [53] Abernethy CS, Amidan BG, Cada GF. Laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish. U.S. Department of Energy, PNNL-13470. 2001. <https://doi.org/10.2172/782074>.
- [54] D. Neitzel, M.C. Richmond, D.D. Dauble, R.P. Mueller, R.A. Moursund, C. S. Abernethy, et al., Laboratory studies on the effects of shear on fish - final report 2000 prepared for the U.S. Department Energy Idaho Operat. Office Under Contract DE-AC05-76RL01830 (2000).
- [55] Vogel S. Life in moving fluids: the physical biology of flow - revised and expanded second edition. 1996.
- [56] Cook TC, Hecker GE, Amaral S, Stacy P, Lin F, Taft E. Pilot scale tests Alden/ concepts NREC Turbine. 2003. <https://doi.org/10.2172/816298>.
- [57] Lin F, Hecker GE, Cook T. Understanding Turbine Passage survival using CFD. HCI Publications, Inc., St. Louis, Missouri. Proc. Hydrovision 2004, 2004.
- [58] R.P. Morgan, R.E. Ulanowicz, V.J. Rasin, L.A. Noe, GB. Gray, Effects of shear on eggs and larvae of striped bass, *Morone saxatilis*, and White Perch, *M. Americana*, *Trans. Am. Fish Soc.* 105 (1976) 149–154, [https://doi.org/10.1577/1548-8659\(1976\)105<149:EOSOEA>2.0.CO;2](https://doi.org/10.1577/1548-8659(1976)105<149:EOSOEA>2.0.CO;2).
- [59] Cada GF, Coutant CC, Whitney RR. Development of biological criteria for the design of advanced hydropower turbines. 1997. <https://doi.org/10.2172/1218126>.
- [60] F. Geiger, U. Stoltz, Guidelines for application of different analysis methods of fish passage through turbines—Impact assessment of fish behavioural aspects, *Nov. Dev. Sustain. Hydropower* (2022), https://doi.org/10.1007/978-3-030-99138-8_9, 105–15.
- [61] G. Cada, J. Loar, L. Garrison, R. Fisher, D. Neitzel, Efforts to reduce mortality to hydroelectric turbine-passed fish: locating and quantifying damaging shear stresses, *Environ. Manage.* 37 (2006) 898–906, <https://doi.org/10.1007/s00267-005-0061-1>.
- [62] (DOE) UD of E. Report to Congress on the potential environmental effects of marine and hydrokinetic energy technologies. Report by Federal Energy Regulatory Commission (FERC). 2009.
- [63] JE. Costa, Hydraulics and basin morphometry of the largest flash floods in the conterminous United States, *J. Hydrol.* 93 (1987) 313–338, [https://doi.org/10.1016/0022-1694\(87\)90102-8](https://doi.org/10.1016/0022-1694(87)90102-8).
- [64] B. Statzner, R. Müller, Standard hemispheres as indicators of flow characteristics in lotic benthos research, *Freshw Biol.* 21 (1989) 445–459, <https://doi.org/10.1111/j.1365-2427.1989.tb01377.x>.
- [65] D. McEwen, G. Scobie, *Estimation of the Hydraulic Conditions Relating to Fish Passage Through Turbines*, NPC001. National Engineering Laboratory, East Kilbride, Glasgow, 1992.
- [66] Turnpenny AWH, Struthers G, Hanson KP, Hanson P. A Uk guide to intake fish-screening regulations, policy and best practice with particular reference to hydroelectric power schemes. 1998.
- [67] B.M. Pracheil, C.R. DeRolph, M.P. Schramm, MS. Bevelhimer, A fish-eye view of riverine hydropower systems: the current understanding of the biological response to turbine passage, *Rev. Fish Biol. Fish.* (2016), <https://doi.org/10.1007/s11160-015-9416-8>.
- [68] H. Spah, *Fishery Biological Opinion of the Fish Compatibility of the Patented Hydraulic Screw from Ritz-Atro pumpwerksbau GmbH*, Chamber of Agriculture North Rhine-Westphalia, Bielefeld, Germany, 2001. Report prepared for client: Ritz-Atro.
- [69] F.S.A. Bracken, MC. Lucas, Potential impacts of small-scale hydroelectric power generation on downstream moving lampreys, *River Res. Appl.* 29 (2013) 1073–1081, <https://doi.org/10.1002/rra.2596>.
- [70] S. Amaral, N. Perkins, D. Giza, B. McMahon, Evaluation of fish injury and mortality associated with hydrokinetic turbines, *Manager.* (2011) 108.
- [71] B.P.M. van Esch, ILY. Spierts, Validation of a model to predict fish passage mortality in pumping stations, *Can. J. Fish Aquat. Sci.* 71 (2014) 1910–1923, <https://doi.org/10.1139/cjfas-2014-0035>.
- [72] Nielsen N, Szabo-Meszáros M. Hydropower and fish - a roadmap for best practice management. 2022. <https://doi.org/10.5281/ZENODO.7805685>.
- [73] Serkowski J, Richmond M, Rakowski C. Nadir pressure exposure estimates for the existing turbines at McNary Dam. Prepared for the U.S. Army Corps of Engineers under a government order with the U.S. Department of Energy Contract DE AC05 76RL01830 2019.
- [74] S. Harding, M. Richmond, *Measurements on hydropower turbine runners. A review of, Situ Meth. Quantify Hydropower Turbine Blade Press. Model. Prototype Scales* (2016). Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830.