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Research paper

Technology Readiness Level assessment of hydrokinetic energy converters

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ABSTRACT

Oceanic, tidal and riverine currents contain vast reserves of renewable hydrokinetic energy. Over the years, numerous innovative hydrokinetic energy converter (HEC) designs have been developed to extract this energy. This paper provides a comprehensive review of HEC designs. Using the U.S. Department of Energy's Technology Readiness Level (TRL) scale, each HEC is assessed to determine its technical maturity and functional readiness, with a corresponding rating assigned. Results indicate that there are fourteen HECs, categorized into riverine, tidal, and oceanic types, distributed across different stages of technological development and corresponding TRL ratings. Among these HECs, two are designed to harness energy from riverine currents, eight from tidal currents, and four from oceanic currents. This distribution suggests a lack of convergence towards a single HEC design capable of harnessing hydrokinetic energy from multiple current sources.

1. Introduction

A significant amount of renewable hydrokinetic energy exists in oceanic, tidal, and riverine currents. According to a 2021 report by the National Renewable Energy Laboratory (NREL), the combined hydrokinetic energy technical resource in oceanic, tidal, and riverine currents in the U.S. is about 368 TWh/yr (Kilcher et al., 2021). This represents nearly 16 % of the total U.S. marine energy technical resource and is equivalent to about 10 % of the electricity generated annually by all 50 states in the U.S. Such an energy resource could significantly contribute to the overall energy supply of countries with long coastlines and extensive river networks such as the U.S., Brazil, Australia, China, Japan, Canada, India, Norway, Egypt and Indonesia (Kim, 2024).

The vast, untapped potential of hydrokinetic and other renewable energy sources, combined with key historical events such as the oil crisis of the 1970s, prompted substantial investments by governments, corporations, and international organizations worldwide in the research and development of renewable energy technologies (Beasley, n.d.). This trend has been further driven by the increasing awareness of climate change, the rising pressure on fossil fuel resources, the global shift toward decarbonization, and the establishment of international climate mitigation agreements, such as the 2015 Paris Climate Accords (Aklin and Urpelainen, 2018). Hydrokinetic energy conversion technology is increasingly recognized as one of the key emerging renewable energy technologies still in the early stages of development (Kilcher et al., 2021). This technology employs Hydrokinetic Energy Converters (HECs) to harness the abundant kinetic energy present in riverine, tidal, and oceanic currents, converting it into electricity or other usable forms of energy.

In recent years, several countries - such as the U.S., Ireland, the Netherlands, the United Kingdom, Spain, Canada, China, and Japan - have led research and development efforts in HECs (U.S DoE; IRENA, 2023), with the aim of making them more economically competitive with other energy sources. HEC development is highly interdisciplinary, drawing on expertise from fluid mechanics, materials science, electrical controls, marine biology, and economics (Ibrahim et al., 2021). Since 2005, several HEC designs have been proposed (Laws and Epps, 2016). Testing sites - such as the Tanana River Hydrokinetic Test Site in Fairbanks, Alaska, U.S.; the Chinese Marine Energy Center on Zhaitang Island, Qingdao, China; and the European Marine Energy Center in Orkney, Scotland (Tanana River Hydrokinetic; Seven Sister Falls Site; Chinese Marine Energy Center (CMEC); EMEC; Hydrokinetic Test Site) – provide real-world environments where full-scale HEC prototypes can be deployed, monitored, and tested. Readers are encouraged to consult the HEC worldwide test center database (Test Sites) for more information.

A comprehensive review of current literature was conducted as part of this study, revealing that many formerly state-of-the-art HEC

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technologies—such as SIMEC Atlantis Energy's SeaGen, Naval Energies' OpenHydro, and Alstom—have been decommissioned, remained inactive, or are no longer in development (Voith Hydro; Alstom formerly TGL; Open Hydro; SeaGen Turbine). This is primarily attributed to technical challenges, environmental obstacles, and uncertainties surrounding governmental regulatory frameworks and market demand (Snieckus; Naval; Shumkov). These factors suggest that, while there is potential for hydrokinetic energy, HEC technologies face considerable challenges in terms of commercialization, economic viability, and technical performance. Simultaneously, the literature review also revealed that new HEC designs/technologies are being proposed, with many at varying stages of technological development, reflecting renewed interest and ongoing innovation in the HEC field. This underscores the evolving landscape in HEC technology development. While previous studies (Ibrahim et al., 2021; Laws and Epps, 2016; Sood and Singal, 2019) have surveyed state-of-the-art HEC technologies and the challenges of hydrokinetic energy conversion, this study offers a comprehensive assessment of the technical maturity and functional readiness of HEC designs/technologies using the Technology Readiness Level (TRL) scale. Given the varying levels of HEC technology development, conducting a TRL assessment is crucial to establish the maturity of existing, emerging and newly proposed designs/technologies.

This study contributes to the current body of knowledge by conducting a comprehensive review of HEC designs capable of harnessing energy from riverine, tidal, or oceanic currents. Key findings from this study, along with the TRL scale, are used to assign each HEC a TRL rating between 1 and 9, reflecting its technical maturity and functional readiness. The structure of the paper is as follows: Section 2 provides a brief description of the TRL scale developed by the U.S. Department of Energy (DOE) for energy projects and devices. Section 3 provides an assessment of each HEC design/technology and assigns a corresponding TRL rating. Section 4 tabulates the TRL rating of each HEC based on the type of current, followed by a detailed discussion. Finally, Section 5 provides a conclusion summarizing the key findings and observations from this study.

2. The U.S. Department of Energy's Technology Readiness Level scale

According to Mankins (2009), the concept of Technology Readiness Levels (TRLs) and its use as a general scale/tool to assess technical maturity of new or novel technologies were first introduced by NASA in the 1970s. The TRL 1–9 scale consists of nine progressive levels with each level representing a key stage in the development and maturation process of a novel technology or system. The U.S. DOE's TRL scale is used in this study as it was developed specifically for renewable & non-renewable energy projects and technologies (U.S. Department of Energy). Table 1 shown below, lists the TRLs 1–9, and a brief description for each TRL. The reader is requested to refer (U.S. Department of Energy) for more details about each objective associated with a particular TRL.

Since its introduction, the TRL scale has become a standard technology assessment tool used by industries such as consumer electronics, power systems, and manufacturing; adopted by organizations such as the U.S. Department of Defense and the U.S. Department of Energy (Straub, 2015; Olechowski et al., 2015).

Table 1
The U.S. Department of Energy's TRL scale (U.S. Department of Energy).

Technology Readiness Level (TRL)	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or system validation in laboratory environment
TRL 5	Laboratory scale, similar system validation in relevant environment
TRL 6	Engineering/pilot-scale, prototypical system validation in relevant environment
TRL 7	Full-scale, prototypical system demonstration in a relevant environment
TRL 8	Actual system completed and qualified through test and demonstration
TRL 9	Actual system operated over the full range of expected mission conditions

3. Assessment of hydrokinetic energy converters using TRLs

3.1. The Verdant Power Tidal Turbine System

Developed by Verdant power, the Verdant Power Tidal Turbine System (VPTTS) is designed to generate power from tidal currents. It consists of three 5th generation free-flow turbines mounted on a single triangular structure (The Roosevelt Island Tidal Energy (RITE) Project). Each turbine is a three-bladed, horizontal-axis turbine mounted on a structure - referred to as the TriFrame™ - which can support up to three turbines (The Roosevelt Island Tidal Energy (RITE) Project). The drive train and the generator are housed in a nacelle, which is supported by a pylon that is, in turn, attached to a riverbed mount (See Fig. 1 on the next page). During operation, the VPTTS aligns with the water flow to generate energy from the flood tide. When a slack tide is detected, the system orients itself by 170 degrees to align with the direction of the ebb flow. The VPTTS is designed to convert kinetic energy of flowing water whose velocities are greater than 1.0 m/s (The Roosevelt Island Tidal Energy (RITE) Project).

As part of the Roosevelt Island Tidal Energy (RITE) project, the VPTTS was successfully tested in the East River tidal strait in New York City, delivering over 312 MWh of tidal power was delivered to the local electrical grid. It also achieved third-party verification based on international standards under the International Electrotechnical Commission for Renewable Energy system (The Roosevelt Island Tidal Energy (RITE) Project). As part of commercialization efforts, there are plans to install the VTTPS off the coast of Holy Island, Anglesey, Wales, UK in collaboration with the Welsh government and Mentor Mon (Morlais: Anglesey tidal energy). Referred to as the Morlais Development Zone Tidal-Stream Energy Project, the installation has the potential to generate about 240 MW of clean, low-carbon electricity (Morlais: Anglesey tidal energy). In summary, the VTTPS successfully demonstrates full scale operation under expected real-world conditions. Therefore, this system is at TRL 9.

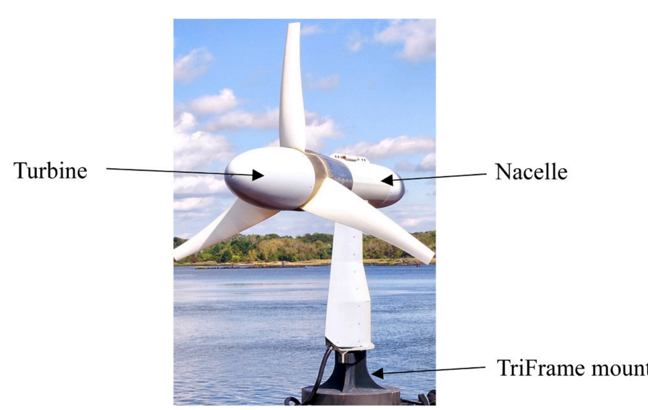

Fig. 1. The Verdant Power Tidal Turbine. Image reference (The Roosevelt Island Tidal Energy (RITE) Project).

3.2. The Kairyu Ocean Current Power Generation System

Developed jointly by the Ishikawajima-Harima Industries Corporation and the New Energy and Industrial Technology Development Organization, the Kairyu Ocean Current Power Generation System (KOCPGS) is designed to harness hydrokinetic energy from ocean currents off the coast of Japan (IHI Demonstrated the World's, 2019). It consists of three cylindrical floats or pods, each approximately 20 m in length and width, with two horizontal-axis turbine rotors, each with a diameter of 11 m (See Fig. 2 on the next page). Each rotor drives a 50 kW generator (Japan Tests Deep-ocean Current Turbines in Search of New Renewables). The Kariyu system is deployed at a depth of 30–50 m below the ocean/sea surface and is moored to an anchor installed on the ocean floor at a depth of around 100 m. The rated current flow speed is 1.5 m/s, and the combined generating capacity (rated output) from the two turbines is approximately 100 kW (Japan Tests Deep-ocean Current Turbines in Search of New Renewables). The system's underwater position is stably maintained by counter-rotating the two turbine rotors (left and right), thereby cancelling the torque associated with each turbine (IHI Demonstrated the World's).

To verify the Kairyu's power-generating performance and underwater behavior, it was towed in the Koshiki Straits off the coast of Noma Misaki Cape (Minamisatsuma City, Kagoshima Prefecture), Japan in July 2017. During this test, it generated power at the rated output of 100 kW for a flow speed of 1.5 m/s (Japan Tests Deep-ocean Current Turbines in Search of New Renewables). In August 2017, the Kairyu system was deployed in the actual Kuroshio Ocean current environment off the coast of Kuchinoshima Island (Toshima Village, Kagoshima Prefecture), Japan. It was anchored to the sea floor (100 m below sea level) using a 280-ton anchor. Deployed over a period of seven days, the Kairyu generated 30 kW of power from the Kuroshio Ocean current, which had an approximate flow speed of 1.0 m/s (IHI Demonstrated the World's, 2019). From 2018–2021, the Kairyu Ocean Current Power Generation System underwent successful demonstrations in the Kuroshio Ocean Current region (Ocean). Data from these tests will be used by IHI & NEDO to develop a full-scale production version of the Kariyu with a power generating capability of 2 MW and turbine blades 40 m long (Japan Tests Deep-ocean Current Turbines in Search of New Renewables). In summary, the operation of the full-scale Kairyu Ocean Current Power Generation System prototype in the actual Kuroshio Ocean Current environment was successfully demonstrated. Therefore, this system is at TRL 7.

3.3. The Generatore Elettrico Marino System

The Generatore Elettrico Marino System (GEMS), developed by Coiro et al. (2017) is designed to generate power from tidal currents. The device operates on the principle of ocean kites (Vermillion et al., 2023) and consists of a submerged floating structure connected to a seabed mount. It features two counter-rotating turbines located on opposite sides of a floating support (See Fig. 3 on the next page). A V-shaped tail section at the rear of the floating support improves stability and

Fig. 3. The Generatore Elettrico Marino System. Image reference (Coiro and Troise, 2012).

facilitates the movement of a self-adjusting winch – a mechanism that tethers the GEM device and allows it to adjust its depth. Initial testing of the system shows it remains unaffected by water depth (Coiro et al., 2017). The GEMS is designed to operate in tidal environment with water depths of 10 m or more and flow speeds of 1.5–4.5 m/s (Coiro et al., 2017).

Prior to full-scale installation, scaled models (1:8 & 1:10) of the GEM system were tested in a laboratory setting which included switching off the turbines to study the system's stability (Coiro et al., 2017). The first full-scale prototype was installed in the Venice lagoon site near Forte Sant' Andrea, Italy. It successfully operated in depths ranging from 9.8 to 15 m and, after 24 h, was able to harness about 2 kW of power at flow speeds ranging from 0.5 to 1 m/s (Coiro et al., 2017). Estimates suggest that it is capable of an average yearly production of 300 MWh of electricity when deployed in a tidal cycle environment with maximum water flow speeds of about 2.6 m/s (Coiro et al., 2017). In summary, the operation of a full-scale GEM system prototype in a relevant environment was successfully demonstrated. Therefore, this system is at TRL 6.

3.4. The Ocean Renewable Power Company's RivGen Power System

The RivGen Power System (RPS), developed by the Ocean Renewable Power Company (ORPC), is designed to harness energy from riverine currents. It is based on the Gorlov helical turbine design (Bachant and Wosnik, n.d.) and consists of several integral components: a turbine generator unit, which includes two horizontal-axis, cross-flow turbines connected by a single shaft to an encapsulated generator; a towable pontoon support structure; power electronics & control system; and underwater power & data cables (RivGen Power System and Integrated Microgrid Solutions-old). The RPS has a stream-wise length of 16.3 m, a cross-stream width of 15 m, and a height of 3.5 m. Each horizontal-axis turbine is equipped with three rotor blades arranged helically, which are connected to a single shaft through six equidistant tri-spokes (See Fig. 4 on the next page). The total turbine capture area (encompassing both turbines) is approximately 18.0 m^2 (RivGen Power

Fig. 2. The kairyu ocean current power generation system. Image reference (https://t.co/npNlvwR5Vd).

Fig. 4. The RivGen Power System. Image reference (RivGen Power System and Integrated Microgrid Solutions-old).

System and Integrated Microgrid Solutions-old). The system has a rated power output of 40 kW at a water velocity of 2.25 m/s, increasing to 80 kW at 3.5 m/s, which is also its maximum operational water velocity (RivGen Power System and Integrated Microgrid Solutions-old).

In November 2007, a 1/3-scale turbine generator unit was successfully deployed and tested as part of a technology demonstration project near Clark's Ledge in the Western Passage, Eastport, Maine (ORPC Maine, 2007). The unit remained in the water for a period of 3–4 weeks. Another key component of the RPS—the unique towable pontoon structure—was successfully tested in 2011 in Cook Inlet near Nikiski, Alaska (ORPC RivGen Power System Overview rev, 2025). Following these initial demonstrations, the first full-scale prototype of the RPS was tested in 2014 in a controlled environment at ORPC's marine energy center in Eastport-Lubec, Maine (RivGen Power System and Integrated Microgrid Solutions-old). This prototype had a power output of 25 kW at a water flow velocity of 2 m/s. In 2019, the first grid-connected RPS was installed in the Kvichak River near Igiugig, Alaska, at a water depth of 5 m (U.S. Department of Energy). This unit has a rated power output of 40 kW. Another identical RPS was installed in the same area in 2023. That same year, ORPC signed an agreement with the Municipality of Chile Chico in the Aysén Region of Chilean Patagonia to install an RPS in the Baker River, Chile (Hydro Review Content Directors). As the full-scale RPS has successfully operated under real-world conditions, it is classified at TRL 9.

3.5. *The Mobile Underwater Turbine System*

Proposed by Tandon et al. in 2017, the novel Mobile Underwater Turbine System (MUTS) combines autonomous underwater vehicle design and hydrokinetic turbine to harvest hydrokinetic energy from the Gulf Stream Ocean current. It is a mobile underwater hydrokinetic energy harvester system which can follow the meandering water current to remain in regions of maximum energy potential. The system also has the ability to harvest hydrokinetic energy from the lateral movement of the ocean current and consists of two major components: a.) the hydrokinetic turbines for power generation; b.) a submarine-style hull to provide a casing for smaller components essential for energy generation and storage, such as batteries, motors, propellers, and electronic systems (See Fig. 5 on the next page). The hydrokinetic turbines are connected to each side of the horizontal plane of the hull. The MUTS also features an anchoring system (Tandon).

The authors conducted a computational study involving modeling, dynamic and feasibility analysis of the MUTS (Tandon et al., 2019). A key detail being explored in this study is the number of hydrokinetic turbines in MUTS. The study revealed that, while increasing the number of turbines can improve the amount of harvested hydrokinetic energy, it can also make the system too bulky. According to the initial design, the MUTS can operate at depths of 50–100 m below sea level and can be anchored to the seabed, opposing an expected ocean current flow of 2 m/s (Tandon et al., 2019). The hull design also contributes to the maneuverability of the MUTS. However, the propulsion of MUTS presents a challenge, as it will use the same harvested hydrokinetic energy to hover into its desired position, which may impact its overall performance (Tandon). In an effort to further develop this system, issues such as turbine size variations and the efficient storage of collected energy are being considered (Tandon et al., 2019). In summary, the technology concept and relevant application of MUTS were successfully demonstrated. Therefore, this system is at TRL 2.

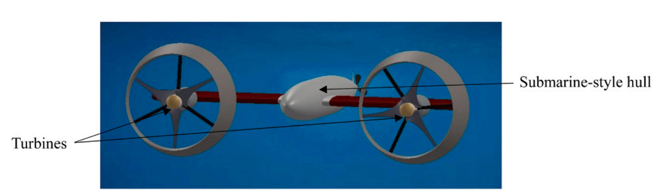

Fig. 5. The Mobile Underwater Turbine System. Image reference (Tandon).

3.6. *The O2 Tidal Energy Turbine System*

Developed by the Orbital Marine Power company, the O2 Tidal Energy Turbine System is designed to generate electricity from tidal currents. It consists of a 74 m long cylindrical floating steel primary structure and two slender secondary structures, in the form of gull-wings, attached on either side (Technology, Orbital Marine. Accessed). The primary structure houses the main power conversion system, while the end of the secondary structure supports a nacelle. A 20 m diameter rotor is connected to each nacelle (See Fig. 6 on the next page). The O2 is anchored using a modular gravity-based anchoring system, with mooring lines. When deployed in tidal streams, a single O2 Tidal Energy Turbine System, with two horizontal-axis, turbines, have a generating capacity of 2 MW. The gull-wing leg design allows the two 20 m diameter rotors to be raised above water for onsite maintenance. It has a low draught of 2.1 m which allows for easy towing and installation (EMEC).

Since July 2021, the O2 Tidal Energy Turbine System has been in operation at the European Marine Energy Center's (EMEC) Fall of Warness grid-connected tidal test site near the Orkney islands, Scotland, UK (Orbital Marine Power O2 at EMEC, 2024). The test site is located in a narrow channel with strong tidal currents which can exceed 3 m/s. Since the start of operation, the O2 system has generated peak power of 2.5 MW (Orbital Marine Power Unveils New 30MW Tidal Energy Project in Orkney Waters, 2024). An assessment of the potential environmental impacts of installation, operation and maintenance of the O2 system was conducted at this site. In 2023, Orbital Marine Power was awarded a 30 MW option agreement from the Crown Estate Scotland, which will allow for the deployment and testing of a 12 unit-array of the 2-MW O2 system at the Westray Firth test site, Orkney islands, Scotland UK (Shumkov, 2024). In summary, the O2 Tidal Energy Turbine System was proven through successful system operations in expected real conditions. Therefore, this system is at TRL 9.

3.7. *The ATIR Tidal Current Turbine System*

Developed by Magallanes Renovables S.L., the floating ATIR Tidal Current Turbine System is capable of generating up to 2 MW of power from tidal currents (Magallanes, 2024). It consists of an upper block (floating platform), vertical block (mast), lower block (nacelle) and two counter-rotating horizontal rotors. The 45 m long upper block contains pumping, electrical and ballast systems. The 10.5 m tall vertical block is a hollow structure connecting the upper and lower blocks; it houses communication and low-voltage cables. The 3 m wide lower block (nacelle) contains mechanical components such as main shaft, ball bearings, gear boxes and electrical generators (Magallanes, n.d). At either end of the lower block, two 19 m diameter counter-rotating rotors, each with three blades, are attached to the main shaft (See Fig. 7 on the next page). The ATIR system is anchored to the sea bed via four mooring lines (catenary chains) connected to gravity-based anchors.

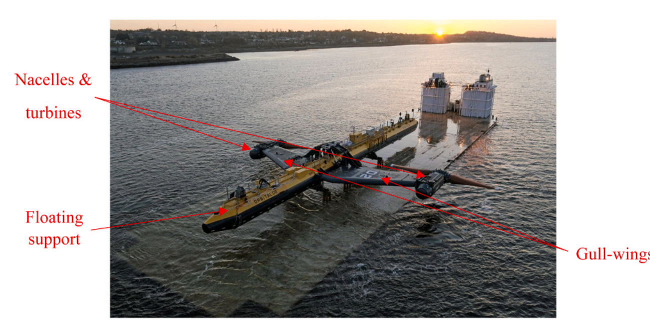

Fig. 6. The O2 Tidal Energy Turbine System. Image reference (EMEC, 2024b).

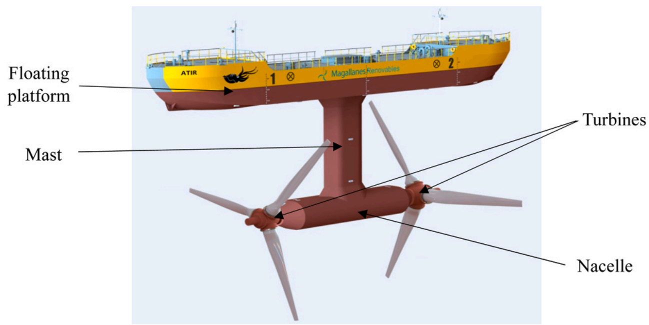

Fig. 7. The ATIR Tidal Current Turbine System. Image reference (Magallanes, 2024).

Each mooring line/chain is approximately 300 m in length (Magallanes, nd).

In November 2014, a 1:10 scale prototype of the ATIR turbine system was installed for testing at the EMEC's Shapinsay Sound test site. After successful scale testing, a full-scale ATIR system was developed in 2017 (Magallanes Renovables, EMEC: The European Marine, 2024). For testing purposes, it was towed by a tugboat to a speed of approximately 2.6 m/s (5 knots), generating a power of about 400 kW in these tests (Díaz-Dorado et al., 2021). The system was then deployed for testing at EMEC's grid-connected Fall of Warness tidal test site in February 2019. This site is characterized by strong tidal currents, with speeds up to 4 m/s (Magallanes Renovables ATIR at EMEC, 2024). The full-scale ATIR system successfully generated power from tidal currents at this site. As part of the testing program, the ATIR was removed for maintenance and performance optimization. It was successfully reinstalled at the same site (Fall of Warness) in September 2022 (Magallanes Renovables ATIR at EMEC, 2024). In summary, the full-scale ATIR system prototype has been successfully demonstrated in the planned operational environment. Therefore, this system is at TRL 7.

3.8. The ocean renewable power company's TidGen Power System

The TidGen Power System (TPS), currently being developed by the Ocean Renewable Power Company (ORPC), is designed to harness energy from tidal currents. Based on the Gorlov helical turbine design (Bachant and Wosnik, n.d.), it consists of the following major components: the TidGen device; the buoyant tension mooring system (BTMS); the grid monitoring & control system; and the power & data cables. The TidGen device features an upper and lower turbine generator unit (TGU), each containing two horizontal axis, cross-flow turbines, and a permanent magnet generator linked through a mechanical driveline (Tidgen Power System). Both the TGUs are secured by a structural chassis and a lateral buoyancy pod (See Fig. 8 on the next page). The BTMS, which consists of the lateral buoyancy pod and the tension mooring system, allows the TPS to operate suspended in the water column while being held beneath the water surface. Each horizontal-axis turbine is equipped with three rotor blades arranged helically, which are connected to a single shaft through three equidistant tri-spokes (Advanced). The current iteration of the TPS design has a stream-wise length of 7.0 m, a cross-stream width of 17.8 m, and a height of 6.0 m. It has a rated power output of 80 kW at a water velocity of 2.25 m/s, increasing to 160 kW at 3.5 m/s, which is also its maximum operational water velocity (In Development).

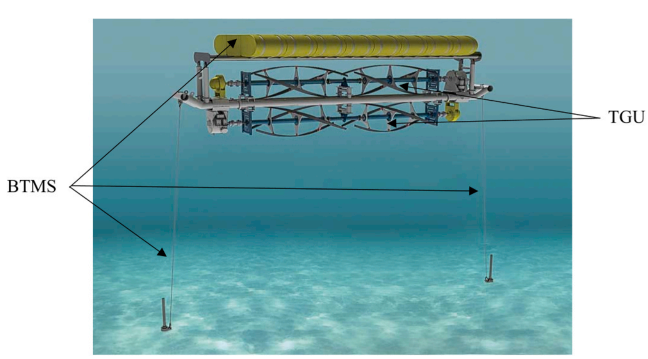

Fig. 8. The TidGen Power System. Image reference (Tidal Power Returns to Maine Waters).

In 2018, a single-turbine version of the TPS was successfully tow-tested at the Cobscook Bay Tidal Energy Test Site near Eastport and Lubec, Maine (Cobscook Bay Tidal Energy Test Site | Tethys and Tethys). Following this, ORPC verified its performance by installing it at the same site for approximately two months in 2020. To refine the design of the full-scale TPS, ORPC deployed and tested the single-turbine version of the TPS at the same tidal test site from May-September 2023 (Cobscook Bay Tidal Energy Test Site | Tethys and Tethys). Performance of the mooring system and environmental data were also collected during this deployment. A full-scale device validation of the TPS is planned to be conducted at the same site in 2025 (Tidgen Power System). As the pilot-scale version of the TPS has been successfully validated in a relevant environment, it is classified at TRL 6.

3.9. The T-2 Tidal Energy Turbine System

Developed by Tocardo B.V., the T-2 Tidal Energy Turbine System is capable of generating power ranging from 100 kW to 250 kW from tidal currents with speeds ranging from 0.4 m/s to 4.5 m/s (Tocardo, 2024a). The T-2 turbine is a medium sized, horizontal-axis turbine with two bi-directional rotor blades, each 5.5 m diameter, made from composite material and attached to the rotor hub and shaft. The nacelle of the T-2 turbine houses the main shaft, which is connected to a permanent magnet direct drive generator that converts rotor motion into electricity (Oosterschelde, 2024). Attached to the nacelle is a vertical, slender support structure that connects it to a horizontal floating frame, which holds the turbine in place (See Fig. 9 on the next page). To prevent overloading, the T-2 turbine enters stall mode when the tidal flow speeds exceed 4.5 m/s. However, it can operate in tidal current speeds up to 6.8 m/s (Tocardo, 2024a). Additionally, the modular design of the medium-sized T-2 turbine allows easy deployment in an array arrangement (World's Largest 5-turbine Tidal Array Installed in the Oosterschelde barrier, 2024).

The first extensive full-scale testing and troubleshooting of the T-2 turbine system were performed at the Eastern Scheldt (Oosterschelde) Storm Surge Barrier (ESSSB) in September 2015 (Oosterschelde, 2024). An array of five T-2 turbines, connected to a 50 m long horizontal structure, was installed at the ESSSB site at Gate Roompot 8. Tidal currents at this near-shore site can reach speeds of 6 m/s. The tidal array power plant is currently in operation and has a total of 1.24 MW installed capacity (Oosterschelde, 2024). To validate the technology in a volatile offshore environment for an extended period of time, a single T-2 turbine attached to a BlueTEC floating platform, was deployed at the grid-connected EMEC's Fall of Warness tidal test site in March 2017 (Tocardo; Tocardo InToTidal at EMEC). The platform with the turbine

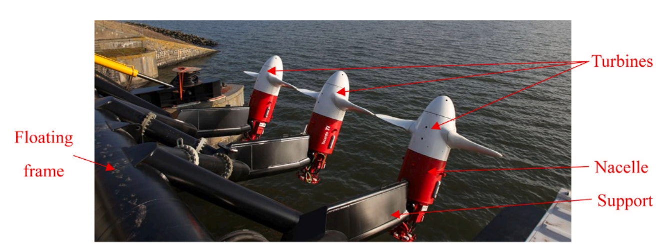

Fig. 9. The T-2 Tidal Energy Turbine System. Image reference (Three Tidal Turbines Installed in Dutch Sea Defences).

was retrieved from the EMEC's test site in November 2017. In summary, a successful demonstration of a full-scale prototype of the T-2 turbine system prototype in the planned operational environment has been performed. Therefore, this system is at TRL 7.

3.10. The AR1500 Tidal Energy Turbine System

Developed jointly by SAE Renewables (formerly: Atlantis Resources Corporation) and Lockheed Martin Corporation, the AR1500 Tidal Energy Turbine System is capable of generating 1.5 MW from a tidal current speed of 3.0 m/s (Lockheed; Tethys). It consists of a single, horizontal-axis turbine measuring 12 m in length, with an attached pitch-abled, 18 m diameter, three-blade rotor (See Fig. 10 on the next page). The hub diameter is 2.4 m, and the blades rotate at 7–15 rpm. The turbine's nacelle houses the main rotor shaft, generator unit, gearbox, bearings and ancillary components (AR1500 Tidal Turbine,). The turbine can be fitted to a variety of support structures, such as a three-legged gravity base, monopile, or pinned structures, using a gravity-stab mechanism. A yaw drive system allows for the realignment of the turbine to the changing tidal direction (AR1500 Tidal Turbine,). The generated electricity is transferred to an onshore substation through undersea electrical cables. The AR1500 Turbine System can be installed in nearshore locations with a minimum water depth of 30 m (AR1500 Tidal Turbine,).

In the summer of 2011, the AR1000 turbine prototype was deployed and tested on Berth 6 of the European Marine Energy Center's (EMEC) Fall of Warness tidal test site (Atlantis Resources Corporation., 2024). Following this successful prototype testing, a single unit of the actual AR1500 turbine system was deployed for operational testing in April 2018 as part of the MeyGen Tidal Energy Project, at the 3.5 km long Pentland Firth grid-connected site between the island of Stroma and mainland Scotland (MeyGen, 2024). After a planned quarter-life maintenance, it was successfully re-deployed at the same site in March 2022 (Tethys, n.d.). Since 2018, this turbine system has supplied about 15 GWh of power to the local electrical grid (MeyGen, 2024). This operational testing phase has also allowed for an assessment of the interaction between the tidal turbine system and local marine life. In summary, the successful operational testing and demonstration of the full-scale AR1500 tidal energy turbine system in the planned environment has been completed. Therefore, this system is at TRL 8.

3.11. The HS1500 Tidal Energy Turbine System

Developed by Andritz Hydro Hammerfest, the HS1500 tidal energy turbine system is capable of generating power between 0.5 and 2.0 MW from tidal current speeds ranging from 1.0 to 4.0 m/s (ANDRITZ HYDRO Hammerfest,). It consists of a single horizontal-axis turbine connected to an open, three-bladed, 18 m diameter rotor (See Fig. 11 on the next page). The nacelle contains the main shaft, a variable-speed conventional generator, gearbox, and ancillary components (Tethys,). For site deployment, the turbine system is attached to a seabed-mounted support structure. Depending on the seabed and tidal characteristics, it can be kept in position either by gravity (ballast weights), pins or pilings (ANDRITZ HYDRO Hammerfest,). The turbine system's design allows for nearshore deployment in water depths ranging from 35 to 100 m. The generated electricity is transferred to an onshore substation through undersea electrical cables. The HS1500 turbine system can also align with tidal ebb and flood directions and maximize energy yield, using variable-speed blade pitching mechanism and the nacelle yawing system (Tethys, n.d.).

In December 2011, a 1 MW pre-commercial tidal turbine prototype, the HS1000, was deployed for testing at the European Marine Energy Center's (EMEC) Fall of Warness tidal test site (ANDRITZ HYDRO Hammerfest, 2024). The prototype operated successfully at this site for about two years before being removed in 2015. During this time, it delivered about 1.5 GWh to the test grid (HS1000 at EMEC., 2024). Based on this prototype, the larger 1.5 MW HS1500 tidal turbine was developed. Three units of the HS1500 were deployed for operational testing as part of the MeyGen Tidal Energy Project at the 3.5 km long Pentland Firth grid-connected site, located between the island of Stroma and mainland Scotland, in April 2018 (Hydro News 30 - MeyGen, 2024). A planned, quarter-life maintenance of the turbine was also performed in 2021. Since 2018, the three units have successfully delivered a combined total power of about 45 GWh to the local electrical grid (MeyGen, 2024). This phase of testing has also enabled the evaluation of potential risks associated with the interaction between the turbine system and local marine life (Tethys, n.d.). In summary, successful testing and demonstration of the full-scale HS1500 tidal energy turbine system in the planned operational environment have been completed. Therefore, this system is at TRL 8.

3.12. The Deep-water In-situ Ocean Current Power Generation System

Proposed by Zhang et al. (2023), the Deep-water In-situ Ocean Current Power Generation System (DIOCPGS) is designed to harness energy from ocean currents with relatively low current speeds ranging from 0.1 to 0.5 m/s, at depths greater than 300 m. The novel system consists of a moored, underwater, chain-driven hydrokinetic turbine (CDHT), a magnetic transmission device, a generator, and an energy storage device (battery). It is designed to generate and deliver reliable power to autonomous underwater vehicles and moored underwater platforms. The CDHT used by Zhang et al. feature deflectable blades

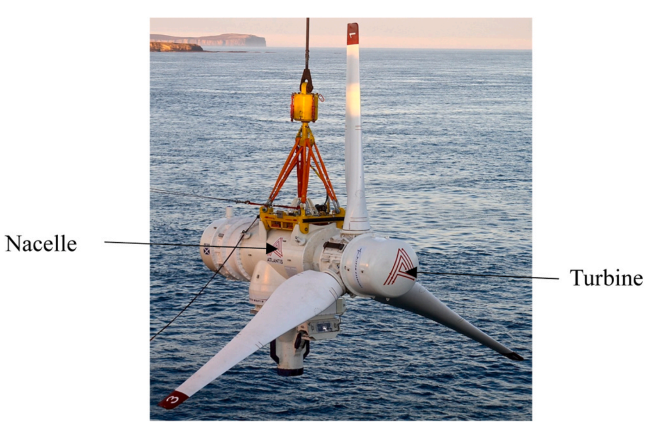

Fig. 10. The AR1500 Tidal Energy Turbine System. Image reference (Lockheed, 2024).

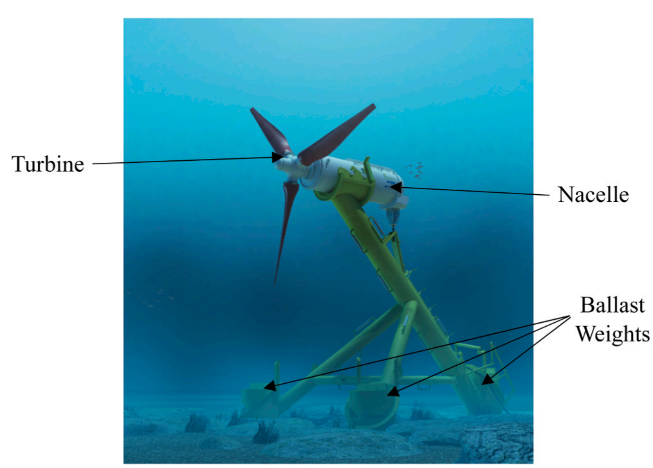

Fig. 11. The HS1500 Tidal Energy Turbine System. Image reference (ANDRITZ HYDRO Hammerfest,).

connected to chain drive, which moves in an oval-shaped path between two axes (van Arkel et al., 2011). The pitch angle of the blades can be adjusted due to the deflectable blade design, allowing the system to harness energy from ocean currents in the downstream region of the turbine (van Arkel et al., 2011). Additionally, the increased power-generating area of the CDHT further enhances its power production capabilities.

A computational study of the deep-water in-situ ocean current power generation system was published by Zhang et al. (2023). In this study, the power supply capacity of the system in-situ was estimated by conducting a comprehensive simulation using a Simulink model. The CDHT simulation model consists of 12 blades, each with a length of 0.3 m, height of 1.0 m, and thickness of 0.005 m, with an axis spacing of 1.5 m. Ocean current data from three locations - A, B and C - were selected, with average current speeds and water depths of: A (0.507 m/s, 374 m), B (0.334 m/s, 409 m) and C (0.174 m/s, 416 m). Simulation results show that the system, over a 24-hour period, can generate and store approximately 670.36 W-h at location A, 218.45 W-h at location B, and 13.9 W-h at location C. In summary, the concept and practical application of the deep-water in-situ ocean current power generation system have been successfully formulated, and a successful simulation study showing proof-of-concept and practical application has also been completed. Therefore, this system is at TRL 2.

3.13. The Circular Cylinder-mounted Bach-type Ocean Current Turbine System

Proposed by Zhu et al. (2019), the novel Circular Cylinder-mounted Bach-type Ocean Current Turbine System (CCBOCTS) is designed to harness hydrokinetic energy from ocean currents in deep water, offshore locations. The system's innovation lies in its ability to generate electricity using both the rotational and vibrational motion of the turbine. This system could be used to power offshore, deep-water structures such as offshore oil and gas platforms (Zhu et al., 2019). The conceptual system consists of a main converter, three electrical generators, two square sliders, ball bearings, belts and pulleys, horizontal & vertical sliders and slideways. The main converter features a horizontal-axis circular cylinder with three modified Bach-type turbines placed adjacent to each other along its length. In the modified Bach-type turbine, the straight-line connection typical of a conventional Bach-type turbine is replaced by a circular cylinder, and the two ends of the cylinder are fixed on two square sliders (Zhu et al., 2019). A ball bearing placed at the center of the slider allows the shaft to rotate freely. By connecting this shaft to a generator, its rotational motion can be converted into electricity. Similarly, by using belts and pulleys, along with two horizontal and vertical sliders, slideways, and two electrical generators, the horizontal and vertical vibrational motion of the shaft can also be converted to electricity.

In the computational study of the novel turbine system performed by Zhu et al. (2019), a single modified Bach-type turbine consisting of two circular arc blades symmetrically installed on a circular cylinder was analyzed. The study numerically solved a situation involving two-dimensional flow past the modified Bach-type turbine. Five turbines with differing blade arc length (L) and blade curvature radius (R), non-dimensionalized with respect to the cylinder diameter (D), were considered: I (1.36, 1.76), II (1.36, 1.30), III (1.36, 0.87), IV (1.50, 1.30) and V (1.23, 1.30). Preliminary results show that, for a non-dimensionalized reduced velocity (U_r) of 14, the type IV turbine can generate a total harnessed power of 33 W/m, followed closely by the type I turbine, which generates 32.5 W/m. Based on these results, the study proposes a conceptual design involving multiple turbines arranged in a staggered fashion (Zhu et al., 2019). Preliminary calculations suggest that for an ocean current flow velocity of approximately 1 m/s, a type I turbine-based array can potentially harness about 155.1 MW when spread over an area of 1 km^2 per unit height. In summary, basic principles of the novel circular cylinder-mounted Bach-type ocean current turbine system have been observed and reported. The technology concept and practical application have been formulated. Therefore, this system is at TRL 2.

3.14. The Vortex Induced Vibration Aquatic Clean Energy Converter

Developed by Bernitsas et al. (2008), the Vortex Induced Vibration Aquatic Clean Energy (VIVACE) converter is designed to convert hydrokinetic energy from riverine currents into electricity. It utilizes the phenomenon of flow-induced oscillation, such as vortex induced vibration (VIV), to capture hydrokinetic power from current speeds ranging from 0.5 to 3.0 m/s. Depending on the size of the converter, it consists of one or more fully submerged, plain circular rigid cylinder(s), supporting linear spring(s), support struts/piles, a power take-off (PTO) system, generator and energy storage (See Fig. 12 below). The PTO system, which includes hydraulics, transmission and electronics components, is housed within the support struts. The cylinder of the converter is placed perpendicular to the flow velocity (Bernitsas et al., 2008). As a result of the VIV, the cylinder oscillates in a perpendicular direction to both its axis and the flow direction. This mechanical energy is transmitted via a gear-belt system to the generator, where it is then converted into electricity. The power output of the converter can be increased by assembling multiple oscillating cylinders/modules in tandem, connected to a generator. The converter is designed for deployment in water depths ranging from 5 to 20 m.

A laboratory-scale model of the VIVACE converter, consisting of a single cylinder unit with a diameter of 0.127 m and a length of 0.914 m, was tested in 2007 at the University of Michigan's low-turbulence, free-surface water channel. The current speed ranged from 0.4 to 1.2 m/s. This test successfully demonstrated proof of concept, generating a peak power output of 11 W (Kim et al., 2021). Following this test, a second laboratory-scale model with adjustable multi-cylinder units and passive turbulence control was successfully tested in 2008, achieving a peak power output of 49.8 W at 1.54 m/s. In 2010, the first 1:1 large-scale prototype (Alpha) of VIVACE, featuring two cylinders with diameters of 0.254 m and lengths of 2.642 m each, was deployed in the St. Clair River, Port Huron, Michigan, to demonstrate performance and gather operational and installation data in a real environment. A second single-cylinder large-scale prototype (Beta-1B) with a more efficient PTO system and improved mechanical components was deployed in the same location in 2012 to investigate the effects of river bed flows on cylinder oscillation. Results from these deployments were used to construct the third large-scale prototype (Oscylator-4), which had four vertical cylinders, each with a diameter of 0.254 m and a length 3.048 m. Weighing 13.5 tons with a concrete base, it was deployed in the same location in 2016. While operating for approximately 11 weeks, it generated about 4 kW at a flow velocity of 1.65 m/s, with power

Fig. 12. The Vortex Induced Vibration Aquatic Clean Energy Converter. Image reference (Kim et al., 2021).

efficiency ranging between 20 % and 34 %. In summary, the VIVACE 1:1, large-scale prototype has been successfully demonstrated in a relevant environment. Therefore, this system is at TRL 6.

4. Discussion

Using the TRL ratings for each HEC from Section 3, the functional readiness and technical maturity of each HEC are assessed in this section. A table (Table 2) is provided below, listing the various HECs, type of current and the assigned TRL ratings.

As seen in Table 2, a total of fourteen HECs exist, each at different levels of technological development. Among them, two HECs can extract energy from riverine currents, eight HECs can extract energy from tidal currents, and four HECs are designed to extract energy from oceanic currents.

At TRL 1, no novel basic principles of HEC have been observed or reported. TRL 1 represents the foundational level where fundamental scientific research is conducted (Mankins, 2009). According to Mankins (2009), the research methodology can either be experimental or computational. Work done at this stage generally leads to the identification and reporting of basic, novel principles of an HEC. TRL 1 is also the lowest level in the technology development & maturation process. Subsequent TRLs in this process involve conversion of the observed basic principles into applied research and development.

At TRL 2, there are three HECs – the Circular Cylinder-mounted Bach-type Ocean Current Turbine System (CCBOCTS), the Mobile Underwater Turbine System (MUTS) and the Deep-water In-situ Ocean Current Power Generation System (DIOCPGS). The novel technology concept of these HECs have been formulated and validated through detailed computational studies and analyses (Tandon, 2024; Zhang et al., 2023; Zhu et al., 2019). In terms of practical application, all three HECs are designed to harness energy from oceanic currents. Currently, there are no HECs at TRL 2 that are capable of harnessing energy from riverine or tidal currents.

Currently, there are no HECs capable of extracting energy from any type of current at TRLs 3–5. These TRLs represent significant milestones in the development and maturation process of novel HEC technologies. According to the TRL scale (U.S. Department of Energy, 2024), TRLs 3, 4 and 5 correspond to proof of concept demonstration, component validation in laboratory settings, and validation in relevant environments, respectively. At TRL 3, experimental work begins in the laboratory, and the results are used to verify any analytical or computational predictions from earlier TRLs (U.S. Department of Energy, 2024). At TRL 4, the primary components of the novel technology are integrated and validated in the laboratory setting. In the case of TRL 5, the complete novel technology system, which includes several components, is tested in a relevant environment (U.S. Department of Energy, 2024). This provides the first demonstration of the system's ability to operate under realistic conditions.

At TRL 6, currently there are three HECs: 1.) The VIVACE, which is capable of extracting energy from riverine currents; 2.) The GEMS and the TPS, both of which are capable of extracting energy from tidal currents. There are no HECs at TRL 6 which are capable of extracting energy from oceanic currents. TRL 6 is a technology demonstration level, where the complete model or prototype of the novel technology system is tested in a relevant environment (U.S. Department of Energy). The VIVACE full-scale prototype was successfully deployed and tested in the St. Clair river (riverine), Port Huron, Michigan (Kim et al., 2021). The GEMS full-scale prototype was successfully installed and tested in the Venice lagoon (tidal) site near Forte Sant' Andrea, Italy (Coiro et al., 2017). The full-scale TPS prototype was successfully deployed and tested at the Cobscook Bay Tidal Energy Test Site near Eastport and Lubec, Maine (Cobscook Bay Tidal Energy Test Site | Tethys and Tethys). Testing in a relevant or real-world environment allows for performance evaluation in multiple realistic scenarios (Mankins, 2009).

Currently, there are three HECs at TRL 7: two HECs (the ATIR and the T-2) capable of extracting energy from tidal currents, and one HEC (the KOCPGS) capable of extracting energy from oceanic currents. TRL 7 represents an important stage in the technology development and maturation process, as it requires an actual, full-scale demonstration of the novel system in its expected operational environment (U.S. Department of Energy). The full-scale ATIR was deployed for testing at the Fall of Warness tidal test site, which has strong tidal currents with speeds up to 4 m/s (Magallanes, 2024). The T-2 turbine system was also deployed at the Fall of Warness tidal test site for full-scale operational testing. Both systems performed successfully in the planned operational environment. The full-scale KOCPGS prototype was successfully deployed and tested in the actual Kuroshio Ocean Current.

At TRL 8, there are two HECs: the AR1500 and the HR1500 turbine systems, both capable of extracting energy from tidal current. According to Mankins (2009), TRL 8 represents the completion of the actual development phase for most components in the novel technological system. The full-scale AR1500 turbine system has successfully operated at the Pentland Firth grid-connected site since March 2022 and has supplied about 15 GWh of power to the local electrical grid (Lockheed, 2024). Three units of the HS1500 turbine system have been operational at the Pentland Firth grid-connected site since 2018, collectively delivering about 45 GWh of power to the local electrical grid (ANDRITZ HYDRO Hammerfest,). Currently, there are no HECs at TRL 8 capable of extracting energy from riverine or oceanic currents.

Currently, there are three HECs at TRL 9: two HECs (the VPTTS and the O2) capable of extracting energy from tidal currents, and one HEC (the RPS) capable of extracting energy from riverine currents. The grid-connected RPS, installed in the Kvichak River near Igiugig, Alaska, at a water depth of 5 m, has successfully delivered 456 MWh to the remote Alaskan village of Igiugig since 2020. The full-scale VPTTS technology successfully operated in the East River tidal strait in New York City as part of the Roosevelt Island Tidal Energy project, generating over 312 MWh of electrical power from the East River tidal current, which was delivered to the local electrical grid. The full-scale O2 turbine system successfully generated a peak power of 2.5 MW at the Fall of Warness grid-connected tidal site near the Orkney islands, Scotland, UK. TRL 9 represents the final stage in the development and maturation process of a novel technological system. It also indicates the successful deployment and operational use of the full-scale (actual) novel technological system in the expected/relevant environment (U.S. Department of Energy).

Although three HECs are currently at TRL 9, indicating readiness for commercial deployment, they have been slow to gain widespread acceptance due to several factors. First, high initial capital costs for installation and infrastructure are a significant barrier, as the HEC technology requires substantial investments in underwater turbines, grid connections, and maintenance infrastructure (LiVecchi et al., 2019). Additionally, concerns regarding the environmental impact of

Table 2
TRL rating for the HECs.

Technology Readiness Level (TRL)	Type of current		
	Riverine	Tidal	Oceanic
9	RPS	VPTTS O2	
8		AR1500 HS1500	
7		ATIR T−2	KOCPGS
6	VIVACE	GEMS TPS	
5			
4			
3			
2			MUTS DIOCPGS CCBOCTS
1			

hydrokinetic systems on marine ecosystems, including potential disruption to fish habitats and local biodiversity, have led to regulatory hurdles and delays in project approvals (Copping et al., 2020). Furthermore, technological challenges in ensuring the reliability and durability of underwater devices, particularly in harsh marine environments, have hindered their commercialization (Xia et al., n.d.). Finally, competition from more established renewable energy sources, such as wind and solar, which benefit from lower costs and better scalability, has made it difficult for commercialization of HEC technologies. For instance, in 2023, according to the International Renewable Energy Agency, the global average cost of electricity from utility-scale solar PV fell to $0.044/kWh and onshore wind to $0.033/kWh (IRENA). In the case of HECs, studies (Jenne et al., 2015; Santos et al., 2019; Klaus, 2020; ACEP) show an average cost of electricity in the range of $0.25/kWh - $0.80/kWh.

The TRLs from 7–9 represent a major stage in the development of a new technology, as they involve actual, full-scale system demonstration, testing, and operation in a range of expected conditions (Mankins, 2009). Across the three types of current listed in Table 2, there are eight HECs between TRLs 7 and 9. Of these, six HECs are capable of extracting energy from tidal currents, one HEC from oceanic current, and one HEC from riverine current. It is important to note that seven HECs, excluding the RPS for riverine current, use the horizontal-axis turbine, a technologically mature turbine design also used in commercial horizontal-axis wind turbines due to their large capacity factor (Rehman et al., 2018).

For the five maturing HECs at TRLs 8 and 9, the following table (Table 3) provides key information about installation cost, annual power yield, and environmental impact. An extensive review of the relevant literature was undertaken to compile this information, which, to the best of the authors' knowledge, represents the most up-to-date data available.

Table 3
Installation cost, annual power yield and environmental impact of maturing HECs at TRLs 8 & 9 (U.S. Department of Energy; MeyGen, 2024; Chase-Israel; Verdant Power New York,; Global Data; Orbital Marine Power, 2018; Ross; Atlantis Resources, 2013; BBC; MeyGen Ltd; Onoufriou et al., 2021; Knowlton; Palmer et al., 2021).

HECs	Current type	TRL	Installation cost (in $) per MWh	Annual power yield (MWh)	Environmental Impact
VPTTS	Tidal	9	9615	312	i.) Does not increase attraction of diving birds to the site. ii.) Device has a low blade strike probability between 0.008 % and 0.009 % for fish.
O2	Tidal	9	2283	17,520	i.) Disturbance and relocation of marine species near the turbine during its operation. ii.) Increased risk of marine animals colliding with the device's moving parts. iii.) Acoustic disturbance during turbine operation.
RPS	Riverine	9	9649	456	i.) No negative effects observed on the local fish population. ii.) The proportion of fish interacting with the device is small. iii.) Degree of injury to the fish from direct foil interactions is to be determined.
AR1500	Tidal	8	2500	1800	i.) Reduction in number of harbor seals during turbine operation. ii.) Foraging and breeding efficiency of marine creatures can be impacted.
HS1500	Tidal	8	2548	2080	i.) Harbor porpoise exhibited significant avoidance during turbine operation. ii.) The sound from turbine operation impacted marine animals' echolocation activity.

5. Conclusion

This study provides a comprehensive review and TRL-based assessment of HEC designs. The assessment reveals that there are fourteen HECs, categorized into riverine, tidal, and oceanic types, distributed across different stages of technological development with corresponding TRL ratings. Amongst these fourteen HECs, two are capable of harnessing power from riverine currents, eight are capable of harnessing power from tidal currents and four are capable of harnessing power from oceanic currents. The study shows that the majority of HECs under development are capable of harnessing energy only from tidal currents. This highlights the need for further research and development of innovative HEC designs capable of harnessing power from riverine and oceanic currents.

From a functional readiness and technical maturity perspective, eight HECs fall within TRLs 7–9, undergoing full-scale system demonstration in relevant environment for riverine, tidal, and oceanic currents. The HECs for tidal and oceanic currents utilize the horizontal-axis turbine technology. The HEC designed for riverine currents, on the other hand, uses a turbine based on the Gorlov helical turbine design. Between TRLs 4–6, three pilot-scale HECs are undergoing system validation: one capable of harnessing power from riverine current and two capable of harnessing power from tidal currents. No HECs exist in this TRL range for oceanic currents. At the conceptual or basic research stages (TRLs 1–3), there are three HECs capable of harnessing power from oceanic currents. No HECs exist at TRLs 1–3 for either tidal or riverine currents. This study highlights the lack of convergence toward a single HEC design/system capable of harnessing power from all three types of current - riverine, tidal, and oceanic. Overall, the study demonstrates that HEC technologies are at various stages of technological development, highlighting a diverse and dynamic field with an evolving technological landscape.

CRediT authorship contribution statement

Zihao Ding: Writing – review & editing, Validation, Resources, Project administration. **Praveen Malali:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Martin Ayala Villavicencio:** Writing – review & editing, Software, Project administration, Methodology, Investigation.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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