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MARINE DEVELOPMENT

REVIEW **Open Access**

Advancements and challenges in tidal stream and oceanic current turbines: an overview of current technologies and future prospects

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Abstract

Tidal power harnesses the predictable movement of ocean tides, offering a reliable source of renewable energy that can significantly contribute to global electricity generation. This paper reviews the primary approaches adopted in tidal energy, including tidal stream generators, tidal barrages, and dynamic tidal power systems. It discusses the operational principles and historical significance in detail. In addition, the paper explores both the similarities and distinctions between tidal stream generators and ocean current turbines. It emphasizes the shared operational principles and design features while also highlighting key differences in their applications and performance characteristics. Recent advancements in turbine technology, particularly in axial-flow and cross-flow designs, have been explored in terms of enhancing efficiency and reducing costs. Despite its advantages, tidal energy faces challenges such as high capital expenditures, environmental impacts, and limited suitable deployment sites. The system advisor model (SAM) is introduced as a tool for simulating the performance and economic viability of tidal energy systems, which facilitates decision-making for project developers. The paper concludes that while tidal power holds considerable promise, further research is crucial for overcoming existing barriers and realizing its full potential in the renewable energy landscape.

Keywords Tidal power, Oceanic currents, Renewable energy, Tidal stream generators, Tidal barrages, Turbine technology, System advisor model, Environmental impact, Economic viability, Marine energy

1 Introduction

Tidal energy is generated by the gravitational interactions between the Earth, the Moon, and the Sun. It is among the most predictable and consistent renewable energy sources. Unlike solar and wind energy, which are subject to weather fluctuations, tidal energy serves as a reliable baseload power supply due to its predictable tidal cycles. This predictability ensures grid stability and resilience, which demonstrates the superiority of tidal energy over other intermittent renewable sources.

Marine energy, which is often referred to as ocean energy or marine hydrokinetic energy (MHK), integrates various technologies that harness the energy carried by ocean waves, tides, salinity gradients, and temperature differences in seawater. This energy is derived based on the movement of water in the world's oceans, and it presents a substantial source of renewable power. A few of the commonly used technologies in this field include wave power converters, tidal turbines, ocean current turbines, and ocean thermal energy converters, which convert the kinetic energy of water into electricity (Khan et al., 2017). Tidal energy converters (TECs) are devices

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that are specifically designed to convert tidal energy into electricity.

A distinctive characteristic of marine energy is its proximity to many major population centers, indicating the potential to supply clean energy at a large scale. Unlike offshore wind, which utilizes the kinetic energy of wind even when situated over water, marine energy primarily captures the natural power of the oceans themselves (Pelc & Fujita, 2002). The global potential of marine energy, including tidal, wave, and ocean thermal energy, is estimated to be between 20,000 to 80,000 terawatt-hours (TWh) annually. 1 TWh corresponds to 3.6×10^{15} J. Specific contributions may include over 300 TWh from tidal energy, more than 800 TWh from marine currents, and up to 80,000 TWh from wave energy. Indonesia, a country with extensive coastal and oceanic geography, holds a massive potential for maximization of marine energy. With 49 GW of recognized ocean energy potential and 727 GW of theoretical potential, Indonesia could significantly benefit from marine energy investments (IRENA, 2020). Developing marine energy technologies is part of a global effort to diversify renewable energy sources and decrease the overall reliance on fossil fuels. There have been increasing projects in the United States and international waters, and most have employed devices such as wave power converters in coastal areas with significant waves, tidal turbines in estuaries, and ocean thermal energy converters in tropical waters with steep thermal gradients (Falcão, 2010). These innovations underscore the increasing significance of marine energy as a future contributor to global energy systems.

The OES Annual Report 2023 (OES, 2024) has highlighted significant progress in the ocean energy sector. A few noteworthy points include the release of a strategic roadmap targeting 300 GW of ocean energy capacity by 2050, technological development with regard to environmental considerations, and ongoing research into the use of ocean energy for desalination processes. The report emphasizes collaborative efforts that have addressed the environmental impacts of ocean energy technologies alongside developments in wave and tidal energy modeling and the economics of Ocean Thermal Energy Conversion. Despite the notable technological advancements, the report underscores the need for continued investment and supportive policies to address issues such as regulatory delays and economic uncertainties. In a broader context, the report illustrates a global commitment to enhancing renewable energy capacity, with over 100 countries pledging to triple their renewable energy resources by 2030, as discussed at the recent COP28 climate summit.

It is worth noting that as highlighted in the latest Energy Institute Statistical Review of World Energy (Energy Institute, 2023), while the production of electricity from wind and solar sources has increased considerably, these renewable sources still account for only a small fraction of the overall growth in global primary energy consumption (Fig. 1). The review analyzes the global energy market data from the previous year. Originally produced by BP (British Petroleum), this review has been providing timely, comprehensive, and objective data to the energy community since 1952. While nuclear energy holds a greater potential contribution than biomass, which is not a net-zero solution due to the transformation of carbon sinks into carbon emissions and the issue of using food-for-energy, especially if drastically scaled up (Hailstone, 2023), hydroelectric power is limited in terms of scalability. The environmental impact of biomass is further analyzed in the discussion section. Geothermal energy, although more prominent than marine energy, holds relatively less potential. This signifies the need for investments in scalable alternatives to wind and solar, such as marine energy.

Notably, China accounts for 35.6% of the world's solar energy consumption in 2023, with the United States at 14.7% and all of Europe, excluding Russia but including Turkey, at 18%, while Australia's contribution is 2.7%. Similarly, China accounts for 38.1% of the world's wind energy consumption in 2023, with the United States at 18.5% and all of Europe, excluding Russia but including Turkey, at 26.4%. Australia has 1.4%.

Marine current power harnesses the kinetic energy from ocean currents driven by factors such as temperature, wind, salinity, and Earth's rotation. These currents are powered primarily by the Sun, and they are relatively stable with minimal fluctuations in speed or direction, making them suitable for energy extraction through turbines (Bahaj & Myers, 2003). These turbines are akin to wind turbines in their operation as they utilize open-flow rotors to convert the kinetic energy of moving water into electricity (Fraenkel, 2002).

Ocean currents contribute to the efforts toward regulation of global climate. However, the environmental impacts of energy extraction from them, such as effects on marine organisms and ecosystem dynamics, are not fully explored. There are persisting turbine-related issues, including blade strikes, entanglement, and acoustic disturbances, which may be attributed to the diverse populations of marine life that use these currents for migration (Gill, 2005). Furthermore, offshore installations require long power cables, which may contribute to electromagnetic pollution in the marine environment (Polagye et al., 2011).

Marine current power holds a substantial global potential, with estimates of 5,000 GW of energy and power densities up to 15 kW/m^2 in certain regions, such as the

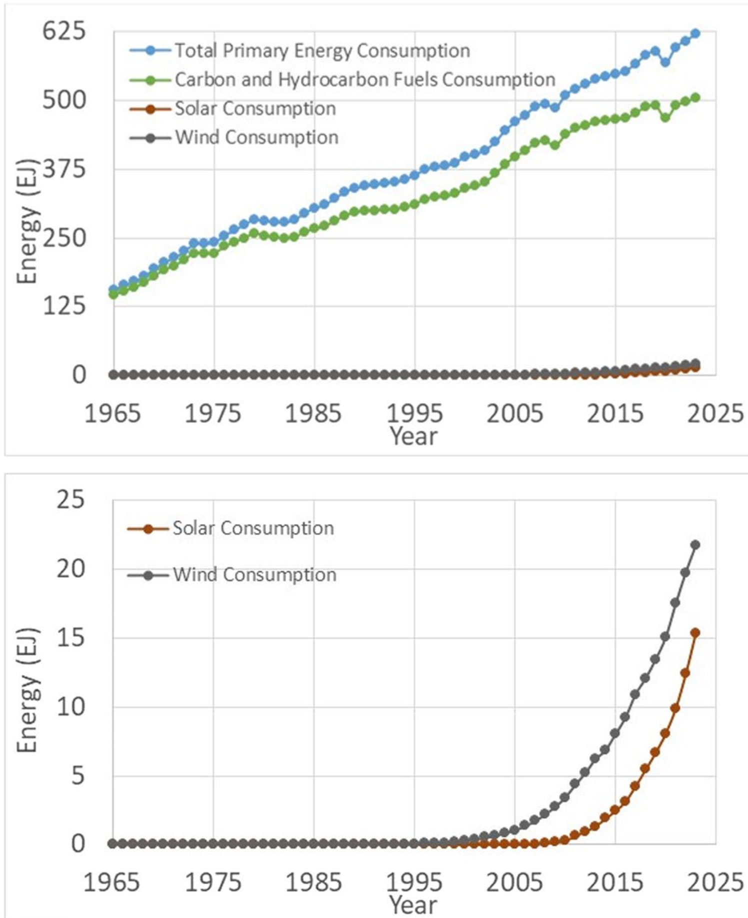

Fig. 1 Contribution of carbon and hydrocarbon fuels, wind, and solar to the total primary energy consumption. Data from Energy Institute (2023)

Florida Straits Current, where energy extraction may account for up to 35% of Florida's electrical needs (IPCC, 2011). Other regions, including Europe, Japan, the United States, and China, are actively exploring the potential of technology to harness this renewable resource (Bahaj, 2011). The European Union (EU) has identified over 100 sites with significant energy potential, estimated to generate 50 TWh/year of electricity from marine currents (Bahaj, 2011).

The technological approaches to extract energy from marine currents are evolving, with several turbine designs under consideration. These include horizontal-axis propellers, underwater kites, and cross-flow Darrieus rotors. Some commonly adopted systems are sea-bed-mounted monopile structures, especially in shallower waters (Stegman et al., 2017). This technology, which first received attention during the 1970s oil crisis, has been the focus of various research projects, particularly in the UK, Canada, and Japan. In these regions, various studies have confirmed the viability of marine current power as a renewable energy source (Bahaj & Myers, 2003). As renewable energy generation becomes a priority in the fight against climate change, marine current power represents a promising, low-impact approach for large-scale electricity generation. Factors such as predictability and consistency indicate its superiority over other intermittent renewable sources (Fraenkel, 2002). With continued advancements in technology, marine current power could play a vital role in meeting global energy demands in the twenty-first century.

Both tidal stream turbines and ocean current turbines are integral components of marine renewable energy, yet they exhibit distinct differences and commonalities that influence their design, deployment, and operational characteristics. Tidal stream turbines and ocean current turbines possess the same operating principle, both harnessing kinetic energy from moving water. They use rotor blades to capture this energy, converting it into electricity, similar to how wind turbines use currents (Bahaj et al., 2007). However, there are a few significant differences. Tidal stream turbines are typically deployed closer to the shore in tidal estuaries or coastal areas where the tidal range is significant. Their proximity to land facilitates easier access for maintenance and installation. Ocean current turbines should ideally be located further offshore, particularly in deeper waters where ocean currents are consistently strong. This can make installation and maintenance more challenging due to harsher marine conditions. Tidal stream turbines generally operate in shallower waters, which can be less harsh in terms of environmental conditions. Ocean current turbines function in deeper, more turbulent waters at high pressure where conditions can be more extreme, leading to greater challenges in terms of mechanical stress and maintenance requirements (Zhou et al., 2017).

Tidal stream turbines experience variable speeds that change with the lunar cycle. Thus, their design must cater to bidirectional operation to capture energy during both incoming and outgoing tides. This reversible operation can complicate turbine design and efficiency (Pelc & Fujita, 2002). Ocean current turbines benefit from more stable and consistent flow speeds, which enables significantly greater efficiency and predictability in energy generation. The continuous nature of ocean currents makes them a more reliable energy source compared to tidal flows, which possess an intermittent nature. The deployment of tidal stream turbines is often restricted by geographic and environmental factors, such as suitable tidal ranges and ecological considerations in coastal areas. Ocean current turbines possess a broader range of potential locations, as ocean currents can be found in various offshore areas, and thus, they are not constrained by geographical limitations (Bahaj et al., 2007). While tidal stream and ocean current turbines share the common goal of converting marine energy into electricity, they differ significantly in terms of operational environments, maintenance challenges, and energy generation characteristics.

The paper provides a comprehensive review of tidal energy technologies, with a primary focus on tidal stream generators, tidal barrages, and dynamic tidal power systems. The paper additionally discusses the emerging role of ocean current turbines, their technological distinctions, and their growing relevance. By exploring recent advancements, economic considerations, and environmental implications, this paper aims to provide a holistic perspective on the challenges and opportunities within the tidal energy sector.

The primary objectives of this work are summarized below.

- Review and analyze recent technological advancements in tidal energy, including innovations in tidal range and tidal stream technologies.
- Examine case studies of operational and planned tidal power plants, such as the La Rance Tidal Power Plant and the Sihwa Lake Power Station, evaluating their performance, environmental impact, and economic viability.
- Evaluate the potential of marine hydrokinetic (MHK) turbines, designed to harness tidal currents and oceanic currents, and discuss their operational challenges and prospects.
- Conduct simulations using the SAM Marine Energy Tidal Model, focusing on how TECs can be deployed to capture tidal energy efficiently.
- Analyze energy performance of different tidal energy system configurations using real-world tidal resource data (i.e., tidal current flow vs. column depth) to assess potential energy output.
- Explore various system configurations, including array designs and turbine placement, to optimize energy capture and minimize operational losses.
- Evaluate the levelized cost of energy (LCOE) for tidal energy systems using SAM's financial modeling tools, incorporating installation, operational and maintenance (O&M) costs (including cabling, permitting, and survey costs).
- Investigate the feasibility and economic viability of using tidal energy as a reliable renewable energy source by comparing the LCOE results with other renewable technologies such as solar and wind energy.

These objectives align with the overarching goal of evaluating the role of tidal energy in the global renewable energy mix and exploring the practical feasibility of the SAM model in assessing and improving tidal energy projects.

2 Backdrop/case study area

Figure 2 shows maps of the amplitude (in meters) for Sa and Ssa ocean signals, which are derived from the GLORYS2v1 reanalysis. The GLORYS2v1 products exclude atmospheric surface pressure effects; these are neither included in the NEMO model forcing nor in the assimilated sea surface height (SSH) data. Consequently, the results agree with IB-corrected sea level data at Sa and Ssa frequencies from both the altimetry and tide gauge observations.

Globally, the total power available from the Moon and Sun on the oceans is estimated at 3.7 TW (10^{12} Watts). After considering the minor dissipation in the atmosphere and the solid Earth, approximately 3.5 TW is dissipated within the ocean (Munk & Wunsch, 1998). For context, the geothermal heat loss is approximately 30 TW, while equator-to-pole ocean heat transport amounts to 2,000 TW. In comparison, solar radiation input (175,000 TW) is greater than tidal power by five orders of magnitude.

A majority of the tidal energy is dissipated within the turbulent bottom boundary layers of marginal seas, where the bottom friction opposes tidal currents. This energy dissipation is concentrated in regions with strong tidal currents, which are highlighted by polygons in Fig. 2c. These areas include the northwest European Shelf, the Patagonian Shelf, the Yellow Sea, the Timor and Arafura Seas, and the Amazon Shelf.

The successful implementation of a tidal energy project significantly depends on the characteristics. High tidal ranges (the difference between high and low tide) and strong flow velocities are vital for maximizing energy generation. The proximity to existing infrastructure, such as ports and electrical grids, significantly reduces construction and operational costs. Environmental factors such as seabed composition and the presence of protected marine areas also affect the site selection. Detailed feasibility studies are required to ensure economic and environmental viability.

Tidal energy potential is highly location-specific, and it is dependent on factors such as tidal range, current velocity, and proximity to energy infrastructure. Notable regions with strong tidal energy potential include:

- Europe. The United Kingdom leads in tidal stream energy development, particularly in regions such as the Pentland Firth and Orkney Islands. France's La Rance tidal barrage serves as a benchmark for large-scale tidal energy projects. A schematic of the La Rance tidal barrage is given in Animalia Life Club (n.d).
- Asia. The Sihwa Lake Tidal Power Station in the Republic of Korea demonstrates the potential of tidal barrages, especially in regions with high tidal ranges.
- North America. Canada's Bay of Fundy, which includes the world's highest tidal range, is a focal point for tidal stream and barrage energy exploration.
- Oceania. Australia and New Zealand are promising sites for future tidal energy development, particularly around Cook Strait.

These case studies illustrate the geographical and technological diversity in harnessing tidal energy. Furthermore, they serve as a basis for assessing deployment challenges and opportunities.

3 Methods

A balanced approach integrating insights from both industry reports and critical academic research is considered in this review. Industry publications often highlight the technological advancements and economic potential of tidal energy, while academic studies include rigorous evaluations of environmental impacts, feasibility, and long-term sustainability. Such a dual perspective ensures a comprehensive understanding of the field. In addition, an analytical tool is presented.

3.1 Literature review

A systematic approach was employed to identify and review relevant literature on the technologies associated with tidal energy. Key databases such as Scopus and Google Scholar were searched using the following keywords—'tidal energy', 'tidal stream generators', 'tidal barrages', 'dynamic tidal power systems', and 'ocean current turbines'.

The inclusion criteria were as follows.

- Peer-reviewed journal articles published within the last 15 years
- Industry reports and white papers that address tidal energy technology and economics
- Studies focusing on the environmental impacts and regulatory challenges of tidal systems

Outdated studies published before 2008, articles with limited relevance to the primary technologies under review, and publications that lack technical or economic analysis were excluded from this review.

3.2 Analytical tools

The SAM was utilized to simulate the performance and financial feasibility of tidal energy systems. The SAM's comprehensive database and modeling capabilities enable scenario analysis, facilitating the comparison of different technologies and site conditions.

(See figure on next page.)

Fig. 2 Maps showing amplitude (in meters) of Sa (a) and Ssa (b) ocean signals, evaluated from the GLORYS2v1 reanalysis. The GLORYS2v1 products exclude atmospheric surface pressure effects; these are not considered in the NEMO model forcing and are corrected in the assimilated sea surface height (SSH) data. These estimates are comparable to IB-corrected sea level observations at Sa and Ssa frequencies from altimetry and tide gauge data. Panel (c) depicts estimates of M2 tidal energy dissipation (W/m^2) caused by bottom friction based on the hydrodynamic tidal model FES2014 (Toulouse Unstructured Grid Ocean model). This model incorporates harmonic constants that are derived from tide gauge and satellite altimetry data for validation during simulations and data assimilation processes. Figures were adapted from Lyard et al. (2021) under the Creative Commons License

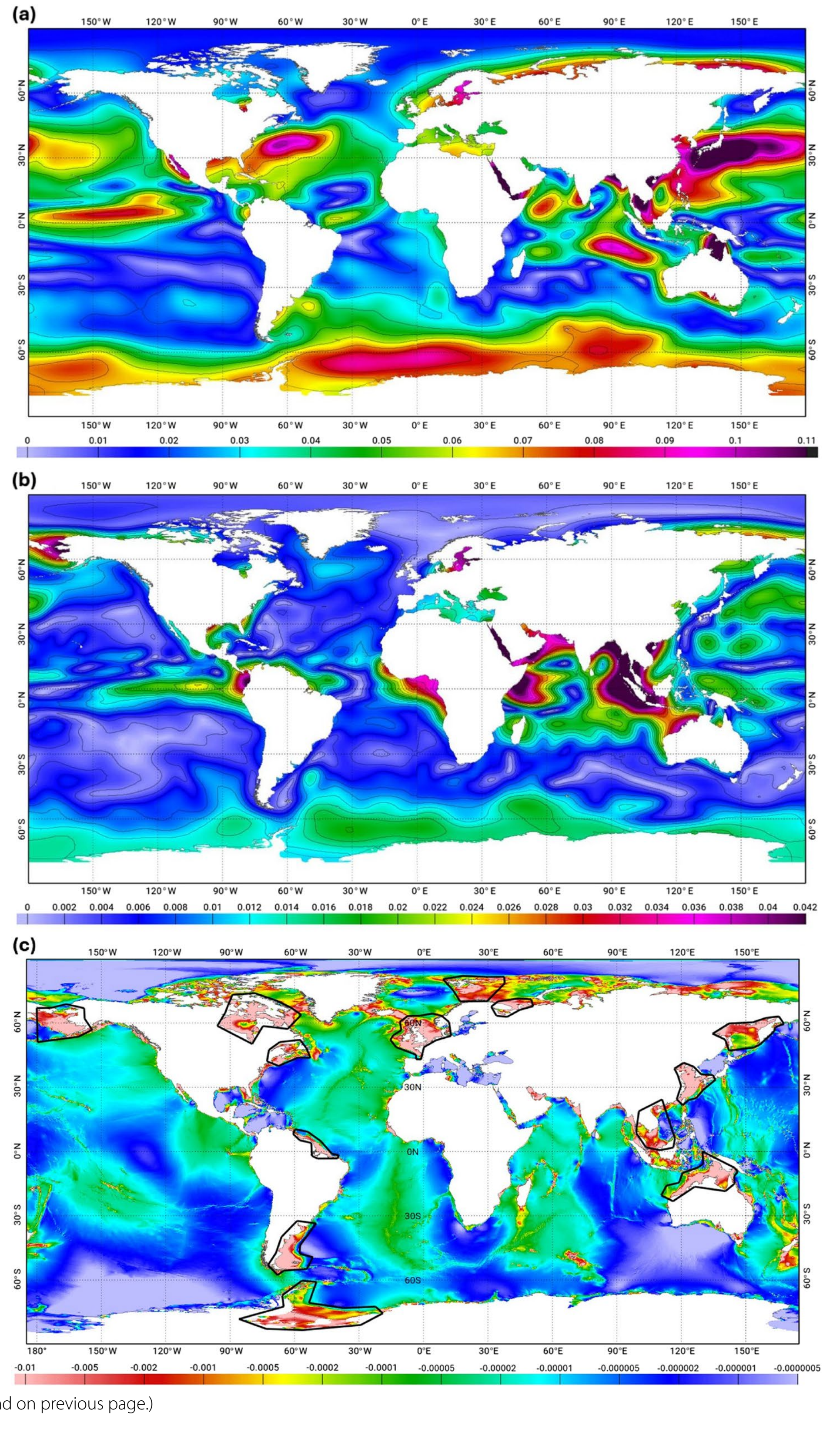

Fig. 2 (See legend on previous page.)

4 Results

4.1 Established developments in tidal power

Tidal power, also known as tidal energy, harnesses the movement of ocean tides to generate electricity using three primary methods–tidal stream generators, tidal barrages, and dynamic tidal power. Among various renewable energy sources, tidal energy is considered the most predictable due to its basis on celestial gravitational forces, which makes it more reliable compared to wind and solar power (Wang et al., 2011). However, challenges such as high costs and limited suitable locations have traditionally restricted its development (Bryden et al., 2004).

Tidal stream generators convert the kinetic energy of moving water into electricity, and they function in a similar manner to wind turbines. Tidal barrages, conversely, leverage the potential energy due to the differences in tidal heights, and they use dams to harness energy (Melikoglu, 2018). Tidal lagoons operate similarly to barrages but use artificial reservoirs, which helps avoid disruptions to existing ecosystems (Roberts et al., 2016). Dynamic tidal power is a theoretical technology that suggests building long dams out into the sea to create tidal phase differences, and thus, it generates significant power based on the interaction of kinetic and potential energy. Historical projects such as the Rance Tidal Power Station in France (1966) and the Sihwa Lake Tidal Power Station in the Republic of Korea (2011) are representative examples of large-scale implementations (Boretti, 2020a). Such projects, though costly, demonstrate the potential of tidal power when combined with technological advancements (Adcock et al., 2015; Pelc & Fujita, 2002).

Recent advances in turbine technologies, including axial and cross-flow turbines, are aimed at reducing and increasing efficiencies (Saini & Saini, 2019). The environmental impact of tidal power, such as the risk to marine life and sediment disruption, is a persisting challenge. These issues can be mitigated through careful site selection and modern design features (Sparling et al., 2018). Tidal energy's carbon footprint is also comparable to that of other renewable sources, which makes it a viable contender in the fight against climate change (Chowdhury et al., 2021).

Lai (2022) classifies tidal energy technology into three types–tidal range, tidal current, and hybrid forms technologies. The European Marine Energy Centre (EMEC, 2024b) identifies six primary categories of tidal energy converters–horizontal-axis turbines, vertical-axis turbines, oscillating hydrofoils, venturi devices, Archimedes screws, and tidal kites. Single- or double-rotor axial flow turbines are currently the most promising devices.

Table 1 shows a comparison of the classifications of tidal energy technologies presented by Lai (2022) and IRENA (2020).

- Tidal Range: Both Lai and IRENA include tidal range technologies, which harness the potential energy from the difference in height between high and low tides.
- Tidal Current: Both classifications acknowledge tidal current technologies, capturing kinetic energy from tidal water flows.
- Hybrid Forms: Lai introduces hybrid forms, and it combines the features of both tidal range and current technologies, a category that is not explicitly mentioned by IRENA.
- Tidal Stream: IRENA specifies tidal stream technologies, and it mainly focuses on extracting energy from fast-flowing tidal currents, which could be considered under Lai's tidal current category.
- Tidal Barrage: IRENA includes tidal barrages, which are large dam-like structures that capture potential energy from tidal height differences, aligning with tidal range technologies.
- Tidal Lagoon: IRENA defines tidal lagoons as enclosed areas that can generate power from tidal movements, a category that is not distinctly highlighted by Lai.

This comparison indicates that while both Lai and IRENA cover fundamental tidal energy technologies, there are differences in terms of categorization and terminology. Lai's inclusion of hybrid forms suggests a broader perspective, whereas IRENA provides more specific classifications, such as tidal stream, barrage, and lagoon technologies.

Figure 3 shows the bidirectional contra-rotating type horizontal axis tidal turbine proposed by Huang et al. (2016). Figure 4 shows a comparison of the power coefficient between single-rotor and contra-rotating rotor turbines.

Tidal power, which is a form of renewable energy harnessed from ocean tides, integrates technologies such as tidal stream generators, tidal barrages, and dynamic

Table 1 Technology type in classifications of Lai (2022) and IRENA (2020)

Technology type	Lai (2022)	IRENA (2020)
Tidal range	✓	✓
Tidal current	✓	✓
Hybrid forms	✓	
Tidal stream		✓
Tidal barrage		✓
Tidal lagoon		✓

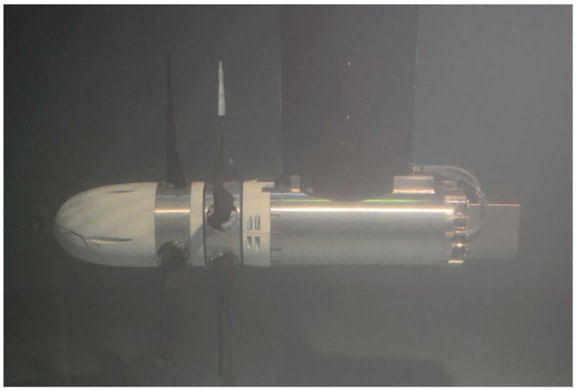

Fig. 3 Unidirectional contra-rotating HATT. Reprinted from Huang et al. (2016), Copyright 2016, with permission from Elsevier

tidal power. Tidal energy is known for its predictability in comparison with other renewable sources such as wind and solar (Boretti, 2020b). Although limited by high costs and site constraints, recent advances in turbine technology and design improvements, such as axial-flow turbines, have indicated good potential for expanding tidal energy's applications (Bahaj et al., 2007).

Axial-flow turbines, which resemble wind turbines, are highly efficient for generating power from predictable tidal flows. However, their durability is often compromised in harsh marine environments with turbulence and debris. Further, the maintenance of axial-flow systems can be complex and expensive, mainly due to submerged locations. Cross-flow turbines, which operate with both unidirectional and multidirectional flows, offer enhanced durability and are less sensitive to debris. Their modular designs make maintenance simpler and enable deployment in shallower waters. Despite the relatively low efficiency, cross-flow turbines are gaining traction due to their adaptability and relatively low lifecycle costs.

Historically, tidal power has been underutilized, with large installations such as the Rance Tidal Power Station in France (1966) serving as the only prominent example. The concept of tidal energy dates back centuries, with examples such as floating mill boats used in rivers and estuaries to harness mechanical power from water currents. By the nineteenth century, tidal mills were extensively used in Europe, mainly for grinding grain. Modern tidal energy development began in earnest with the La Rance tidal power station in France, commissioned in 1966. This project demonstrated the feasibility of large-scale tidal energy but also highlighted the main challenges, such as high capital costs and ecological impacts. In recent years, the advancements in turbine technology and floating systems have revitalized interest in tidal energy.

Recent advances in turbine designs, specifically axial-flow turbines, have been pivotal to the development of both tidal and oceanic current power systems. Boretti (2020b) highlights that MW-level turbines for oceanic currents are similar to tidal turbines in terms of design but face additional challenges, such as deployment in deep waters and variable flow speeds.

The recent research on marine hydrokinetic turbines focuses on open-rotor, axial-flow designs similar to wind

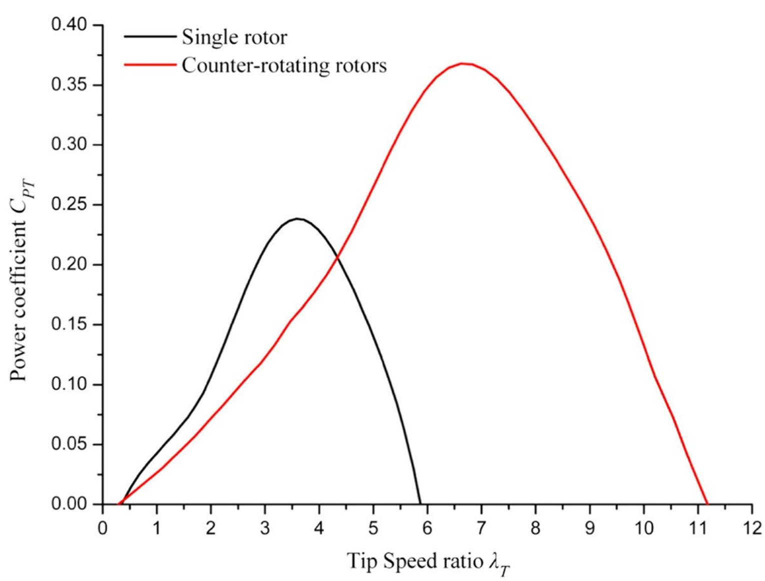

Fig. 4 Comparison of power coefficient between single rotor and contra-rotating rotor turbines. Reprinted from Huang et al. (2016), Copyright 2016, with permission from Elsevier

turbines. These turbines are often anchored to the ocean floor and require optimal conditions, such as stable oceanic currents, moderate depths, and proximity to shore, to yield maximum efficiency. Unlike tidal currents, oceanic currents flow continuously, presenting a reliable, albeit slower, energy source due to the density of water (Yuce & Muratoglu, 2015; Zhou et al., 2017). Although ocean currents hold greater potential, they are not fully explored, warranting further research to optimize turbine placement and operation (Boretti, 2020b).

Some technological challenges persist, particularly in turbine efficiency. While wind turbines can good achieve efficiencies of up to 0.45, marine turbines often operate below this value, with designs such as the Bahaj et al. (2007) rotor achieving a power coefficient of 0.45 at optimal conditions. Enhanced versions, such as ducted turbines, have shown the potential to exceed the Betz limit, but they also increase costs (Werle & Presz, 2008).

Environmental concerns such as the effects on marine ecosystems and corrosion from saltwater are significant hurdles. Tidal turbines may directly affect marine life through blade strikes and changes in sediment flows, though newer designs possess the necessary features to mitigate these effects (Sparling et al., 2018). While tidal and oceanic current energy technologies remain in their infancy, recent advancements in turbine design and site optimization have paved the way for broader adoption. Continued research and pilot projects are critical to overcoming the remaining technical and environmental challenges (Boretti, 2020b).

Tidal and oceanic current power generation relies on capturing the kinetic energy of moving water. Most common methods use axial-flow turbines, which possess a similar design to wind turbines but are adapted to the marine environment due to the high density of water. The basic power equation for a tidal or oceanic current turbine (Boretti, 2020b) is

$$P = 1/2 \cdot \eta \cdot \rho \cdot A \cdot V^3$$

where P is the power generated (in watts), H is the turbine efficiency (or power coefficient), ρ is the water density (typically 1025–1030 kg/m^3 for salted water, and 1000 kg/m^3 for freshwater), A is the swept area of the turbine rotor ($A = \pi \cdot r^2$, where r is the rotor radius), and V is the flow velocity of the water.

The efficiency of the turbine is typically governed by the Betz limit, which indicates the maximum theoretical efficiency for a wind or water turbine in free flow. For tidal or oceanic current turbines, the maximum efficiency is 59.3% or 0.593. This limit applies to any turbine that extracts energy from a fluid flow and was derived by Betz as follows:

$$H_{max} = 16/27 \approx 0.593$$

However, marine turbines often achieve relatively low efficiencies due to additional losses such as mechanical and electrical conversion losses. Therefore, the actual power coefficient η is typically below this theoretical maximum.

The relatively steady nature of oceanic currents in comparison with tidal flows, makes them a promising source of renewable energy. While tidal currents vary according to the lunar cycle, ocean currents tend to flow continuously, though at slower velocities. Given that the kinetic energy in a fluid is directly proportional to the cube of the flow velocity, even a small increase in water velocity dramatically increases the potential power output. It is worth noting that while higher flow velocities lead to an increase in potential power output for stream generators, this is not a limiting factor for lagoon or barrage systems because they operate based on water volume and head difference, not flow velocity. A small increase in velocity may lead to a significant increase in power output, which is a major reason optimal site selection is crucial in both tidal and oceanic current energy projects.

In practical terms, marine turbines witness losses due to mechanical and electrical inefficiencies (Boretti, 2020b), which can be represented as

$$\eta_{total} = \eta_{aero} \times \eta_{mech} \times \eta_{elec}$$

where η_{aero} is the aerodynamic (or hydrodynamic) efficiency, which is constrained by the Betz limit, and η_{mech} accounts for mechanical losses, such as friction, and η_{elec} accounts for losses in the electrical generation system, including the generator and power electronics.

The tidal energy, which is primarily driven by the gravitational forces of the Moon and the Sun, has been utilized for centuries, with early tide mills dating back to Roman times (Spain, 2013). Modern tidal power plants such as the La Rance Power Station (France) and Sihwa Lake Power Station (South Korea) have demonstrated good potential for use in large-scale tidal energy production. However, their advancements have been limited to a few key projects (Boretti, 2020a). While the focus has shifted toward tidal stream and ocean current technologies, which are theoretically more scalable and environmentally feasible, these technologies largely remain in the development or demonstration phase.

Tidal energy is harnessed using two main methods–tidal range and tidal stream. Tidal range systems, like barrages, capture energy based on the height difference between high and low tides, while tidal stream systems utilize the turbines to capture the kinetic energy of moving water, similar to wind turbines. A notable example of tidal range technology is the La Rance Tidal Power Plant, which has been operational since 1966, with a capacity of 240 MW. It produces approximately 540 GWh annually with a capacity factor (CF) of 0.26. This plant exemplifies the success of tidal energy despite environmental and economic challenges (Boretti, 2020a; Frau, 1993).

Another noteworthy project, the Sihwa Lake Tidal Power Station in the Republic of Korea, is the world's largest tidal power plant with a capacity of 254 MW. This station was completed in 2011, and it generates power during the inflow of tides. However, its CF remains similar to La Rance at 0.25, indicating the variability and limits of tidal range technology (Bae et al., 2010; Boretti, 2020a).

The future of tidal energy may be dominated by tidal stream and oceanic current turbines, which do not require large barrages and can seamlessly operate in open water. These systems are still in the early stages but hold good potential mainly due to their smaller environmental footprint compared to tidal range technologies (Boretti, 2020a). Tidal stream projects, such as the MeyGen Tidal Energy Project in Scotland, have shown considerable progress but remain limited in terms of scalability. MeyGen's first phase involved four 1.5-MW turbines producing 13.8 GWh in 2019, with a CF of 0.26, indicating the challenges of scaling up this technology (Lewis et al., 2019).

Although the turbines hold good theoretical potential, practical challenges such as high operational costs, maintenance in harsh marine environments, and the need for reliable arrays of turbines should be addressed.

Tidal power is one of the most capital-intensive renewable energy technologies. For example, the construction costs of La Rance were approximately $3,400 per kW, and those for Sihwa Lake were $1,170 per kW. These figures are significantly greater than those for solar and wind power, making tidal energy less attractive from a purely economic perspective (Boretti, 2020a). However, due to its predictability, tidal energy possesses the ability to serve as a consistent energy supply. The levelized cost of electricity for tidal stream turbines is estimated to be between $0.27 and $0.51 per kWh, which is significantly greater than that of other renewable sources such as solar and wind (Boretti, 2020a). The cost of tidal energy may be reduced with technological advancements and larger-scale deployment. However, it is uncertain if it can become economically competitive with other renewables soon. Although tidal power is a reliable and predictable source of renewable energy, it has struggled to scale beyond a few major projects, mainly due to factors such as high costs, environmental concerns, and technological limitations. Tidal streams and oceanic current turbines hold good potential for future development. However, significant research and demonstration projects are required to make these technologies commercially viable. The success of tidal power projects such as La Rance and Sihwa Lake demonstrates the long-term feasibility of tidal energy. However, the lack of suitable sites and economic challenges hinder its widespread adoption. A key factor that affects the bankability of tidal energy projects is the perceived unproven reliability of tidal energy technology in terms of scale, which makes financial institutions hesitant to invest due to potential risks and uncertain returns.

4.2 Recent technology demonstrators and concepts

Among the several technology demonstrators, Orbital Marine Power Ltd (EMEC, 2024a) stands out as one of the most promising. This Scotland-based company focuses on developing tidal energy turbine technology with the potential to significantly reduce the cost of tidal stream energy. Orbital has pioneered a unique floating tidal turbine that is designed for simplified, safe, and cost-effective manufacturing, installation, access, and maintenance. In addition, the system uses small, low-cost workboats for all offshore operations, reducing overall costs.

Building on the success of its earlier model, the SR250, the company developed the SR2000, a 63-m, 500-tonne, 2 MW commercial-scale turbine that is highly suitable for tidal array deployment.

The SR2000 was first deployed at EMEC's tidal test site in October 2016. With a rated capacity of 2 MW, the SR2000 established itself as the world's most powerful tidal turbine, achieving a peak of 2.24 MW export power early in its commissioning at the EMEC substation. During its testing, the SR2000 achieved several significant milestones. Over 3 GWh of renewable electricity was exported to the Orkney grid during the first 12 months of continuous generation. Considering a 2-MW turbine operating at full (rated) capacity for one year would produce 17.52 GWh of energy, this represents a CF of 17.2%. The SR2000 maintained rated power in 2-m significant wave heights and continued generation in waves up to 3.5 m, withstanding waves over 6 m and generating over 100 kW from wave power alone. Maintenance interventions by Orbital's operational team were performed in under 40 min from the quayside to the turbine.

In September 2018, the SR2000 was removed to pave the way for Orbital's next innovation, the Orbital O2. This 2-MW turbine features a 72-m floating superstructure, supporting two 1 MW turbines on either side. The turbine's 18-m-long legs hold 100-tonne nacelles at a depth of 14 m, and the 20-m-diameter rotors span 600 m^2, which is 50% larger than the SR2000. A key innovation in the O2 is its full wing leg configuration, which allows the rotors to be raised above the water for easy access and maintenance. The O2 uses a gravity-based anchoring system that repurposes ballast from the SR2000.

Alongside key project partners, the European Commission's Horizon Europe Programme has selected Orbital to lead a multi-turbine tidal energy project called EURO-TIDES. The project aimed to accelerate the commercial deployment of Orbital's floating tidal stream technology by developing manufacturing solutions for series production, optimizing long-term operations and maintenance, and gathering extensive performance data. EURO-TIDES will also promote commercial-scale tidal projects in French waters, which would subsequently expand Orbital's portfolio in the UK and overseas. The European Commission has identified transitioning from single-turbine deployments to multi-turbine arrays as a crucial step in scaling tidal stream energy to meet net-zero targets in the UK, EU, and beyond.

The authors believe that considerable advances in marine energy production, particularly from oceanic currents, could be realized by implementing ducted axial-flow turbines (Elbatran et al., 2016; Münch-Alligné et al., 2018; Park et al., 2023). Designed to accommodate the unique directional characteristics of oceanic and tidal currents, these turbines would be designed such that they would operate unidirectionally for oceanic currents, which will maintain a stable flow direction, and bidirectionally for tidal currents, wherein the flow direction reverses with each tidal cycle. Although several studies have established the practicality of reversible turbines, largely due to their relevance in pumped hydroenergy storage systems (Wang et al., 2020; Zhang & Tang, 2022), there has been increasing attention toward the design of ducted hydrokinetic turbines, specifically for marine environments (Elbatran et al., 2016; Münch-Alligné et al., 2018; Park et al., 2023). Despite no commercial deployment of such ducted turbines in marine settings, the emerging research underscores their potential to optimize the energy captured from ocean currents and tides.

The ducted axial-flow turbine approach advocated by the authors involves mounting these turbines on concrete foundations on the seafloor, wherein they would be both stable and accessible. This infrastructure simplifies the maintenance processes; turbines could be temporarily lifted for repairs and routine servicing, streamlining their operational management. In comparison with conventional free-flow turbines, ducted turbines present several distinctive benefits, particularly in enhancing flow capture efficiency and power generation. The flow intake expands the capture area, which leads to an increase in the velocity at the turbine's entry. This enhanced flow velocity is critical given that the power output is proportional to the cube of the velocity of incoming water. Therefore, even a modest increase in the velocity can produce a significant gain in the energy output. This enables the use of smaller turbines capable of generating significant power. The smaller scale of these turbines improves their overall manageability, making them easier to install, maintain, and replace, in contrast to larger free-flow turbines that must withstand more direct exposure to ocean or tidal currents variability.

Furthermore, smaller, ducted turbines pose fewer environmental concerns because they can be designed to minimize disruption to local marine ecosystems, including the effects on marine organisms and sediment. By limiting the environmental footprint, ducted turbines align well with the sustainability objectives in marine energy deployment, thus offering a promising approach to balance efficient energy generation with ecosystem conservation.

Thus, the ducted axial-flow turbine approach offers both increased energy production efficiency and enhanced environmental stewardship. As such, it serves as a strategic and viable solution for advancing marine energy technology, particularly in response to the consistent directional flow of oceanic currents and the variable nature of tidal currents. This framework underscores a forward-looking vision for marine renewable energy, emphasizing technological innovation and ecological responsibility.

4.3 Simulations of tidal energy systems using SAM

The SAM-based marine energy tidal model is designed to simulate the performance and financial viability of tidal energy systems, specifically tidal energy converters. The SAM, developed by the National Renewable Energy Laboratory (NREL), provides a comprehensive framework to analyze the conversion of energy from ocean tides into electricity and to estimate the associated costs (NREL, 2024a, 2024b).

The SAM analysis involves the use of validated models to derive novel findings for specific locations where the resource has been assessed.

The key features of the SAM marine energy tidal model are as follows.

Performance and Resource Modeling The model requires detailed inputs regarding the tidal resource at the site of deployment, specifically a table of tidal current flow versus column depth. This input is critical for assessing the change in tidal resources with depth and analyzing how TECs will perform in these conditions. By factoring in tidal current speeds at different depths, the model simulates the energy that can be captured by turbines across a tidal cycle, which directly affects the system's energy yield.

Array Design For systems with multiple TECs, the SAM enables the configuration of the array layout by specifying the x–y positions of the turbines. This helps users simulate how the placement of turbines affects the performance of the entire array. The spacing between turbines is critical for minimizing energy losses caused by wake effects—where turbines downstream capture less energy due to the disturbance caused by upstream turbines (Dallman & Neary, 2014). Optimizing turbine placement helps improve energy capture and reduce operational losses.

Loss Factors The SAM considers various losses that may directly hamper the efficiency of tidal energy systems. Array spacing losses: As mentioned, the interaction between the turbines within an array may reduce the overall efficiency. Resource prediction uncertainty: The uncertainties in tidal resource estimates can directly affect the performance predictions of the system. The SAM allows users to incorporate this uncertainty into the calculations to generate more realistic energy estimates. Electrical transmission losses: Energy losses during transmission from the offshore site to the onshore grid are factored into the calculations.

LCOE Calculation The SAM's tidal energy model is integrated with its financial modeling tools to estimate the LCOE, a critical measure of the economic feasibility of energy projects. The model allows users to input installation and operating costs, and it calculates the LCOE according to the total cost over the system's operational life. This is important for a fair comparison of tidal energy projects with other renewable energy technologies (LaBonte et al., 2013). The LCOE calculation in SAM is aligned with standardized methodologies for reporting the performances of marine and hydrokinetic technologies (LaBonte et al., 2013). This ensures consistency in evaluating the economic viability of tidal energy projects, accounting for the unique costs of marine installations such as deployment, maintenance in harsh environments, and high capital expenditure of TECs.

The National Renewable Energy Laboratory's SAM (NREL SAM) is a versatile tool used to evaluate the performance and economics of renewable energy projects. Two key metrics calculated in SAM are the LCOE and the CF, both essential for comparing technologies like tidal, wind, solar, and more.

The LCOE represents the per-unit cost ($/kWh) of building and operating an energy project over its lifetime. It accounts for all costs (capital, operations, and maintenance) and energy production.

$$\text{LCOE} = \text{Total Lifetime Costs}/\text{Total Lifetime Energy Output}$$

where the total lifetime costs include capital expenditures (CAPEX), fixed and variable O&M, financing costs, and decommissioning costs. The total lifetime energy output is the cumulative energy generated over the project's operational life.

SAM's LCOE methodology is as follows. The inputs required are project lifetime, discount rate or weighted average cost of capital (WACC), CAPEX and O&M costs, and energy production data (based on simulations using resource input files and system design). The approach used for calculation is as follows. The SAM computes cash flows for every year of the project's life. It discounts these cash flows to their present value and divides the total discounted cost by the total discounted energy production. SAM allows for detailed modeling, including the variations in resource availability, system degradation, and inflation-adjusted costs.

In comparison with other renewables, the LCOE for solar energy is often lower, mainly due to the declining module costs and minimal O&M expenses. Onshore wind projects typically possess competitive LCOEs due to high CFs and reduced technology costs. For onshore wind, learning rates are typically around 10%–15% cost reduction per doubling of capacity. The LCOE for tidal energy is generally higher due to high CAPEX (due to underwater infrastructure) and site-specific challenges. Detailed cost analysis for various technologies can be found in the NREL Annual Technology Baseline (ATB) reports, which specify LCOE benchmarks.

The CF measures the actual energy output of a system as a percentage of its maximum possible output if it operates at full capacity 24/7.

$$\text{CF} = \text{Actual Energy Output}/\text{Maximum Possible Energy Output} \times 100$$

where the actual energy output is calculated from simulated or observed data, and the maximum possible energy output is the product of installed capacity and the total hours in a year.

SAM's CF methodology is defined as follows. The inputs required are resource data (e.g., tidal current profiles, wind speeds, solar irradiance), system specifications (e.g., turbine efficiency for tidal, inverter efficiency for solar), and operational assumptions (e.g., downtime for maintenance). The approach used for calculation is as follows. SAM uses resource input files (e.g., TMY files for solar or tidal flow data) to simulate hourly energy production over a year. CF is computed as the ratio of this simulated production to the theoretical maximum.

In comparison with other renewables, the CFs of solar PVs ranges from 15% to 25%, depending on location and system design. Onshore wind has CFs in the range of 30%–40%. Higher wind speeds and consistency push CFs to 40%–50% in offshore wind. Tidal energy has competitive CFs, ranging from 30% to 50%, owing to predictable tidal cycles and high water density.

The NREL SAM documentation provides a comprehensive guide to the methodologies and assumptions used in SAM (NREL, 2024b). The NREL Annual Technology

Baseline (ATB) offers data on LCOE, CAPEX, and CFs for various renewables (NREL, 2024c). By utilizing SAM's robust modeling capabilities, stakeholders can conduct detailed economic and performance analyses, which helps make informed decisions and establish fair comparisons between renewable technologies.

4.4 Sample marine energy tidal model application

The SAM's tidal model facilitates decision-making for project developers and policymakers by providing estimates for both energy production and cost. Furthermore, it helps researchers optimize array designs and configurations by testing different layouts, spacing, and turbine designs. This approach helps improve efficiency and reduce the cost of tidal energy, which is currently higher than other renewable sources such as solar or wind.

A critical challenge associated with tidal energy systems modeled in SAM is the high-cost in comparison with other renewables. The SAM model includes provisions for estimating these costs accurately. For example, the model uses real-world data to provide more accurate LCOE estimates for tidal projects, which often witness higher operational and maintenance expenses due to the harsh marine environmental conditions (Dallman & Neary, 2014). However, tidal energy systems benefit from their predictability. Unlike wind and solar energy, which are subject to variability due to weather conditions, tidal energy is primarily driven by predictable celestial forces. This makes it a reliable source of renewable energy with a consistent production potential (Boretti, 2020a).

By incorporating detailed resource data and financial parameters, the SAM model allows users to explore the potential of tidal energy systems for specific sites. The ability of the model to simulate different configurations and predict financial outcomes helps address issues such as high costs and design optimization, which are critical to the future development of tidal energy. The SAM marine energy tidal model serves as a valuable tool for simulating the performance and economic viability of tidal energy systems. By integrating tidal resource data, array configurations, and financial modeling, the SAM helps developers and researchers assess the feasibility of tidal energy projects accurately. The model's focus on the LCOE provides a standardized framework for comparing tidal energy with other renewable technologies, which ensures that tidal energy projects are evaluated consistently and transparently.

The resource is provided as frequency of occurrence for velocity or time series of velocity for a typical year. From tide gauge measurements, it has been established that the monthly average mean sea levels vary from year to year and from decades to decades, with many periodicities up to quasi-60 years well described in the literature. This leads to variability in electricity production not only within a single day but also day-to-day, month-to-month, and year-to-year.

The SAM reference models include one axial and one vertical axis turbine, and they are described by a curve of power vs. velocity, and then sample resources given as one velocity vs. frequency, or the time series of velocity for a few locations. It is worth noting that the SAM model is not validated, and therefore, all the results are only qualitative.

Figure 5 shows a sample time series for one location (South of Point Mackenzie) and the power curve for one axial flow turbine (bottom fixed, Taut Mooring, Permanent Magnet Synchronous).

Table 2 shows the computed financial and technical parameters, while Fig. 6 presents the breakdown of the LCOE in the different components.

For the nine different locations, the computed LCOE varies from 84.69 to 571.32 ¢/kWh, depending on the specific velocity distribution. Ideally, different turbines should be employed for different velocity distributions. The optimal power output of tidal turbines depends on the matching between the power curve and frequency of occurrence of specific velocities, and the potential to work efficiently with direct as well as reverse flows (Boretti, 2020b).

In the case of one vertical flow turbine of type cross-flow floating and slack-mooring with rated power 80.62 kW (Fig. 7), SAM returns for the same location an LCOE of 908.82 ¢/kWh, for the breakdown of Fig. 8.

As discussed previously, the axial flow tidal turbines and oceanic current turbines possess several differences as well as similarities. Oceanic current turbines have some downfalls, but in addition to the ability to be placed in many locations, they benefit from a nearly constant velocity.

The NREL Electricity Annual Technology Baseline (ATB) provides a comprehensive and accessible set of technology-specific cost and performance metrics across various research and development (R&D) scenarios, resource types, and locations for electricity-generating technologies. These metrics include current data and projections extending to 2050. It is worth noting that the NREL has not yet incorporated marine energy into its ATB. This absence suggests that marine energy technology may be lagging behind its competitors.

4.5 Key findings

The review highlights several key findings.

- Technological Advancements: Axial-flow and cross-flow turbines have demonstrated significant improve-

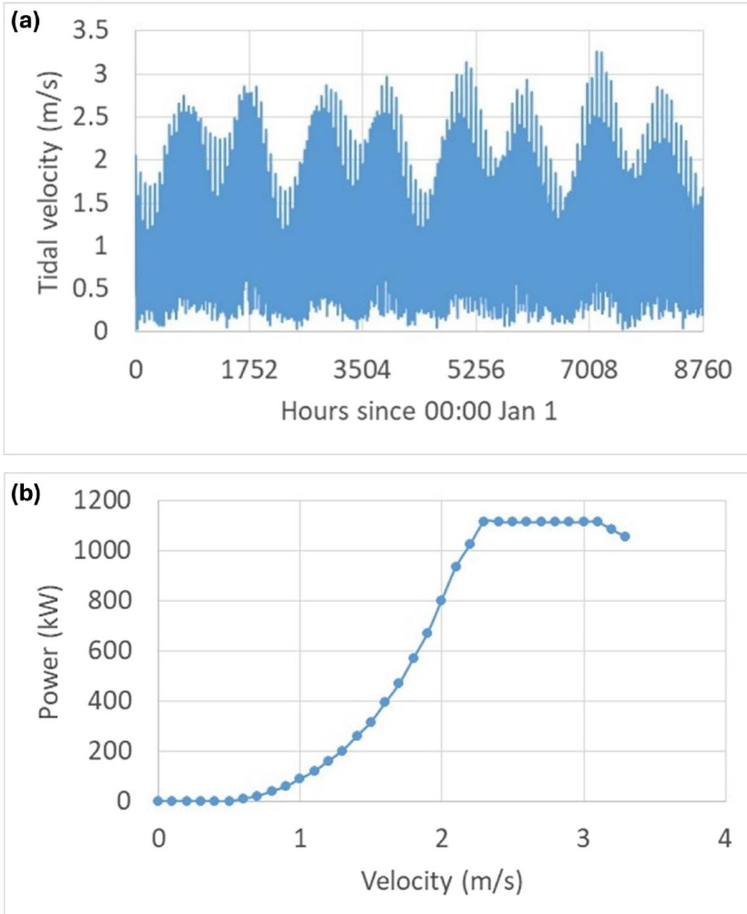

Fig. 5 SAM sample inputs and outputs. **a** Time series for South of Point Mackenzie. **b** Reference axial-flow turbine power curve. Data from NREL (2024b)

Table 2 Computed financial and technical parameters

	Metric or costs	Costs per capacity	LCOE
Annual energy production	2,275,316 kWh		
Average power per device	260 kW		
System capacity	1,115 kW		
CF	23%		
LCOE	125.65 ¢/kWh		
Capital cost	$13,860,559.31	$12,431/kW	$0.66/kWh
Device cost	$4,231,116.60	$3,795/kW	$0.20/kWh
Balance of system (BOS) cost	$8,512,656.38	$7,635/kW	$0.40/kWh
Financial cost	$1,116,786.34	$1,002/kW	$0.05/kWh
O&M cost	$1,362,080.09/yr	$1,222/kW/yr	$0.60/kWh

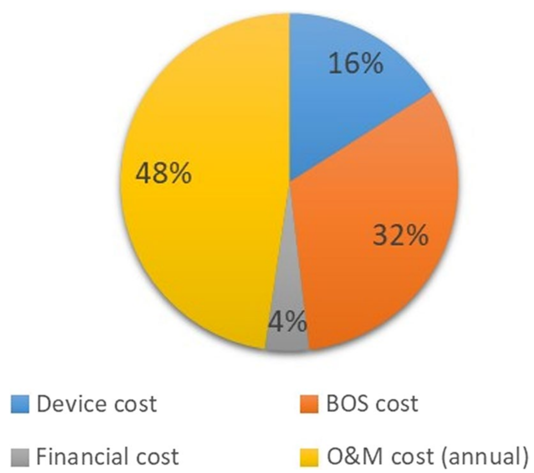

Fig. 6 Breakdown of the LCOE for the reference axial flow turbine. Computational results by SAM (NREL, 2024b)

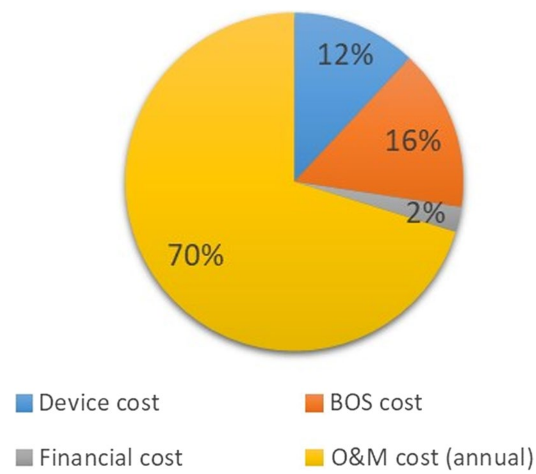

Fig. 8 Breakdown of the LCOE for the reference vertical flow turbine. Computational results by SAM (NREL, 2024b)

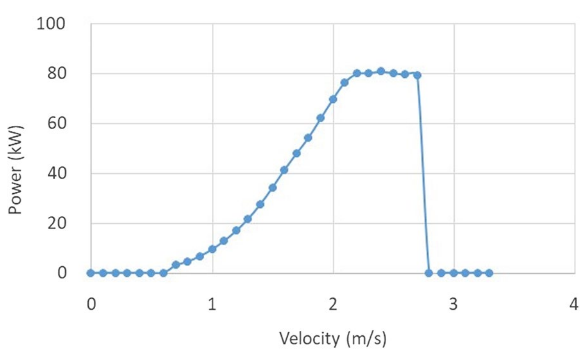

Fig. 7 Reference vertical turbine power curve. Data from NREL (2024b)

ments in efficiency, durability, and adaptability to varying flow conditions.

- Economic Viability: The LCOE for tidal systems remains high compared to wind and solar but can be potentially reduced through economies of scale and technological innovation.
- Environmental Considerations: Tidal barrages pose significant ecological challenges, such as methane ebullition from increased estuarine sedimentation (Chanton et al., 1989), while tidal stream generators have a comparatively lower impact but require site-specific assessments.
- Deployment Trends: Europe leads in tidal energy deployments, with emerging interest in Asia–Pacific and North America.

Several interactive tools and databases are available to explore the regions of tidal energy deployment. The Marine Energy Atlas, which was developed by the NREL, is an interactive mapping tool that allows users to explore potential marine energy resources in the United States, including tidal energy (NREL, 2024d). The TidEA by Noveltis (TIDEA, 2025) provides tidal energy assessments, offering maps and reports on tidal currents and power densities across various regions worldwide. Aquatera's Tidal Database (Aquatera, 2025) includes data on over 11,000 sites across more than 150 countries, focusing on tidal streams, river estuaries, and ocean currents. These resources can assist in identifying and assessing potential sites for tidal energy projects across the globe.

5 Discussion

5.1 Differentiation between tidal barrages and lagoons

Tidal lagoons have gained increased popularity in recent years. There are structural and operational differences between tidal barrages and lagoons, as well as environmental and economic trade-offs.

Basics Tidal barrages are dam-like structures that are built across the mouth of a tidal estuary. They create a reservoir by trapping water at high tide and then release it through turbines to generate electricity. They typically operate in ebb generation (releasing water as the tide recedes) or flood generation (allowing water to flow in as the tide rises). Some advanced designs can operate in both directions limited to estuaries with a natural funneling shape and significant tidal range. Tidal lagoons are enclosed areas of the sea created by constructing embankments in coastal regions, which form an artificial reservoir. Lagoons generate electricity by allowing tidal flows to move water in and out through turbines. They can be designed for either one-way or two-way generation cycles. The Swansea Bay Tidal Lagoon, for example, is designed for dual operational mode, and it functions as a pumped storage system in addition to tidal energy generation. Furthermore, they are more flexible in site selection as they can be built along open coasts, not necessarily requiring estuaries.

Environmental Impacts Tidal barrage can significantly alter estuarine ecosystems by restricting natural tidal flow. It may lead to sedimentation, habitat loss for marine and bird species, and changes in water salinity and quality. Another critical impact is fish mortality due to turbine passage. Tidal lagoons are considered less intrusive as they can be located in areas with fewer environmental sensitivities. However, they still affect the marine ecosystems within the lagoon and disrupt local species' movements. Sediment transport and coastal erosion patterns may also be affected.

Economic Comparison Tidal barrages typically involve higher initial construction costs due to the complexity of building across estuaries. Factors such as long lifespan and predictable energy output make them cost-effective over time. The limited locations suitable for construction may restrict deployment. Permitting processes for tidal barrages can be lengthy and costly. For instance, the Swansea Bay Tidal Lagoon project faced significant permitting challenges, and it involved several key milestones. The project team submitted its application for a development consent order to the Planning Inspectorate in 2014. The first preliminary hearing to discuss the examination procedure took place on June 10, 2014. The UK Government granted development consent for the project on June 9, 2015. Despite receiving development consent, the project faced significant financial challenges. The estimated capital cost was £1.3 billion. The concerns surrounding the project's value for money led to the UK Government's decision to financially pull out from the project in June 2018. This example illustrates the complexities and potential obstacles in the permitting and funding processes for tidal barrage projects, which can be both lengthy and costly. Tidal Lagoons are more scalable and potentially less expensive to construct, depending on location. Modular construction enables the implementation of smaller initial projects with gradual scaling. A more favorable public perception due to reduced ecological disruption can facilitate approval and investment.

5.2 Advantages and challenges of tidal energy

Tidal energy offers the following advantages.

Predictability Tidal energy stands out for its exceptional predictability. Unlike solar and wind energy, which depend on weather conditions, tidal cycles are governed by the gravitational forces of the Moon and the Sun, making it highly reliable, with precise forecasts of tidal movements possible years or even decades in advance. This predictability ensures a stable and consistent energy output.

Baseload Power Generation Tidal energy provides baseload power, which is a continuous and steady energy supply that meets the minimum electricity demand. Unlike other renewables that require energy storage solutions or backup systems to address intermittency, tidal power operates on regular and cyclical patterns, ensuring a dependable energy flow. This characteristic helps maintain grid stability and reduce reliance on fossil fuel-based baseload systems.

Integration with Other Technologies Tidal energy systems can complement other renewable energy sources to enhance the overall grid efficiency. Furthermore, it can be integrated with solar and wind systems to offset periods when these sources are less productive (e.g., night for solar, calm days for wind). The predictable nature of tidal energy makes it suitable for pairing with energy storage technologies such as batteries or pumped hydro storage. This synergy can store excess power during peak tidal generation and release it during off-peak periods. With recent advancements in smart grid technologies, tidal energy can seamlessly balance supply and demand, complementing intermittent renewables to optimize energy distribution.

These unique characteristics position tidal energy as a key player in achieving a sustainable and resilient energy future.

While tidal energy offers unique advantages, such as predictability and baseload power, it faces the following critical challenges.

High Initial Costs Capital expenditures for tidal energy projects are significantly greater than those for wind and solar. Furthermore, innovative financing models and government subsidies are essential for scalability. Green bonds and public–private partnerships, which are successfully implemented in offshore wind projects such as those financed by Ørsted (n.d), could be effective financing mechanisms.

Environmental Trade-offs Mitigation strategies, such as fish-friendly turbine designs and sediment management, are necessary to address ecological concerns, including potential strikes on cetaceans and habitat disruption. Marine mammal effects, such as strikes, potential noise pollution, and habitat disruption, must be carefully considered and mitigated. Whales play a crucial role in vertical nutrient movement and may suffer disproportionate effects on the carbon cycle from injuries (Gilbert et al., 2023; Pearson et al., 2023; Pershing et al., 2010).

Technological Barriers Issues such as biofouling, sediment dynamics, and turbine durability in harsh marine environments remain unresolved.

A few strategies that can be used to overcome these challenges include increased R&D investment, cross-industry collaboration, and supportive policy frameworks.

5.3 Climate change influence on tidal energy

While a collapse of the Atlantic Meridional Overturning Circulation (AMOC) is not expected to occur any time soon (Parker, 2016), an AMOC collapse may certainly have profound consequences on tidal systems.

Altered Tidal Patterns AMOC collapse could disrupt tidal patterns globally because it may change the oceanic flow dynamics. This may reduce the efficiency of tidal energy systems in certain locations with a shift in tidal amplitude and current speeds. Predictable energy generation, which is a major advantage of tidal systems, could be undermined by these changes.

Climate Feedback Loops A weakened or collapsed AMOC may lead to severe climate shifts, including cooling in the North Atlantic and warming elsewhere. These changes could hamper the structural integrity and operational reliability of tidal installations. Factors such as rising sea levels and changing coastal dynamics, which are often associated with AMOC weakening, could pose risks to tidal infrastructure through increased flooding and erosion.

Ecosystem Disruptions The AMOC plays a significant role in nutrient cycling and marine ecosystem health. Its collapse could lead to shifts in fish populations, and this may potentially hamper the ecosystems near tidal installations and create further environmental challenges for tidal energy projects.

Some strategies can be adopted to mitigate these issues. The first is ensuring that the amount of energy extracted by tidal systems is within sustainable limits to avoid significant alterations to oceanic flow dynamics. The second is using advanced climate and hydrodynamic models to predict how tidal energy installations might interact with large-scale ocean systems like AMOC. The third approach is developing tidal systems that can adapt to changing water dynamics, ensuring resilience in the face of shifts in ocean currents and tidal patterns. Another approach is coordinating with international bodies to monitor and manage the cumulative impacts of tidal energy projects on ocean circulation systems, including AMOC.

While tidal energy offers immense benefits, understanding and mitigating its potential risks, such as interactions with the AMOC, are critical for sustainable development. Balancing energy extraction with ocean health could ensure that tidal power contributes positively to the renewable energy mix without unintended consequences for the global climate system.

5.4 Learning curve effects

Learning curve effects may boost the progress of tidal technology.

Current Status of Tidal Technology Tidal energy is currently in the early stages of commercial deployment in comparison to more established renewables like wind and solar. High initial capital costs (CAPEX) dominate due to the need for robust underwater structures, turbines, and site-specific installations. The O&M costs are elevated due to the challenging marine environment.

Mechanisms Driving Cost Reductions Technological innovations in turbine design, materials, and mooring systems reduce costs, and modular designs for tidal devices improve scalability and simplify installation. As more tidal projects are deployed, manufacturing processes become standardized, and this may subsequently lead to bulk procurement and lower production costs. The experience gained from deploying and maintaining tidal systems has helped establish streamlined processes and reduced downtime. Enhanced modeling and site selection reduce the risk of underperforming installations. Further, investments in R&D and pilot projects accelerate the adoption of cost-effective solutions.

Empirical Evidence of Learning in Tidal Energy Early projects, such as the MeyGen array in Scotland, have demonstrated cost reductions through iterative deployment phases. The EMEC has facilitated knowledge sharing, which has helped developers refine designs and improve performance.

Comparison to Other Renewables Solar PV has a learning rate of ~22%, driven by large-scale manufacturing, standardization, and global adoption. Onshore wind exhibits a learning rate of ~15%, and it benefits from incremental improvements and scaling. Offshore wind, which shares some technological similarities with tidal energy, initially required high costs, which are rapidly declining (~ 10%–15% learning rate) due to advancements in turbine size, floating platforms, and mass deployment. Learning rates for tidal energy are estimated to range between 10%–20% in the early stages, with the potential to enhance further as deployment scales and technical challenges are overcome through various approaches. Due to the predictable nature of tidal energy, performance improvements are more focused on reducing CAPEX and O&M costs rather than addressing intermittency.

Challenges to Achieving Learning Curve Gains in Tidal Energy One of the main challenges is the limited deployment. Tidal energy projects require significant upfront investment, which can potentially hinder rapid scaling. The site-specific nature of tidal systems limits the opportunities for standardization. Permitting and environmental assessments are time-intensive and costly, which slows

Table 3 Comparison of unidirectional and bidirectional turbines

Feature	Unidirectional turbines	Bidirectional turbines
Flow direction	One direction (ebb or flood)	Both directions (ebb and flood)
Energy capture	Limited to a single flow direction	Maximized by capturing both flow directions
Design complexity	Simpler	More complex (rotating blades or yawing)
Maintenance requirements	Lower	Higher due to moving parts
Cost	Lower CAPEX and O&M	Higher CAPEX and O&M
Suitability	Ideal for unidirectional tidal currents	Suitable for bidirectional tidal currents

deployment and learning progress. Harsh underwater conditions necessitate high durability and reliability, and this may subsequently increase the costs and technical complexity.

Strategies to Accelerate Learning The investment in R&D is fundamental. It is important to focus on innovative turbine designs, material science, and automated maintenance technologies. Funding should be directed from appropriate sources, such as NERC in the UK or similar bodies in other regions, which are mandated to support renewable energy research. Fostering public–private partnerships to fund initial deployments can create pathways for cost reductions. International collaboration through platforms such as EMEC to pool insights and best practices. Furthermore, permitting processes can reduce project timelines and associated costs.

By leveraging learning curve effects, tidal energy technology can achieve significant cost reductions, improving its competitiveness with other renewable energy sources. Sustained investment, policy support, and iterative deployment will be crucial to maximizing its potential.

5.5 Types of tidal turbines

Tidal turbines, which are used to harness energy from tidal currents, are designed such that they can seamlessly operate in unidirectional or bidirectional flow configurations. These designs may directly affect the turbine's operational efficiency, complexity, and suitability for specific tidal sites. Table 3 provides a summary of the major differences between these devices.

Unidirectional Flow Tidal Turbines Unidirectional turbines are designed to generate power when water flows in a single direction. They are typically oriented to maximize the energy extraction during either the ebb tide (outgoing tide) or the flood tide (incoming tide). These turbines possess some unique characteristics. Fixed orientation: They are installed in a static position aligned with the primary tidal current direction. Simpler design: Unidirectional turbines have fewer moving parts and are simpler to construct and maintain in comparison with bidirectional systems. Efficiency in strong currents: These turbines are particularly effective in locations where one direction of flow is significantly stronger or more predictable than the reverse direction.

Unidirectional turbines offer the following benefits. Cost-effective: Their simpler design reduces manufacturing and maintenance costs. Durability: With fewer moving parts and no requirement for yaw mechanisms, these turbines are more robust. Ideal for unidirectional tidal sites: They are well-suited for estuaries or other locations with a dominant tidal flow direction. However, these turbines also possess some disadvantages. Energy loss: Power generation stops during reverse tidal flow, reducing overall energy output. Site constraints: These turbines are effective only in environments where one direction of flow dominates. Therefore, unidirectional turbines are most effective in estuaries or channels with a dominant flow direction and minimal flow reversal, e.g., small-scale tidal projects or areas with natural funneling of water.

Bidirectional Flow Tidal Turbines Bidirectional turbines are designed to generate electricity during both ebb and flood tides, harnessing energy regardless of the water flow direction. These turbines also possess some key characteristics. Reversible blades or turbine orientation: These systems either possess blades that can rotate to adapt to flow direction or use yaw mechanisms to reorient the entire turbine structure. Innovations such as teardrop or plate blade profiles enable efficient bidirectional operation without yaw mechanisms. Continuous operation: They are capable of operating throughout the entire tidal cycle, maximizing energy capture. Bidirectional flow tidal turbines have the following advantages. Higher energy yield: By capturing energy from both tidal directions, these turbines improve overall CFs. Versatility: They are suitable for a wider range of tidal sites, including those with bidirectional currents. Enhanced predictability: They generate power more consistently, aligning with the cyclic nature of tides. These turbines also have some disadvantages. Higher costs: The added complexity of bidirectional designs increases manufacturing and maintenance expenses. Increased wear and tear: Moving parts and mechanisms for blade rotation or yawing may experience higher failure rates or degradation. Efficiency loss: Some designs may be less efficient than unidirectional systems due to the compromises made to accommodate reverse flow. Therefore, the best locations for bidirectional turbines are open tidal areas with significant flow in both directions (straits, tidal basins), e.g., tidal lagoons or barrages where water flow alternates predictably.

Future trends may include hybrid designs, technological innovations, and deployment growth. Some manufacturers are exploring turbines that can adapt between unidirectional and bidirectional modes to optimize performance based on site conditions. Advanced materials and control systems are being actively developed to reduce costs and improve the reliability of bidirectional turbines. As tidal energy scales, bidirectional systems may become the standard mainly due to their ability to maximize energy capture across a broader range of sites.

Both unidirectional and bidirectional tidal turbines play critical roles in advancing tidal energy technology. The choice between these depends on factors such as site-specific conditions, project economics, and energy capture goals.

5.6 Comparison of tidal energy with biomass

Regarding the environmental impact of biomass, it is noteworthy that while biomass energy is often considered renewable because it relies on organic materials that can regenerate over time, its role in achieving net-zero emissions is complex and mainly depends on factors such as feedstock source, lifecycle emissions, land-use impacts, and integration of carbon capture technologies.

Biomass energy is not inherently carbon–neutral because burning organic matter releases stored carbon dioxide (CO_2) into the atmosphere. If biomass is sourced from unsustainable forestry or agricultural practices, the carbon that is released during combustion may not be offset by regrowth or replanting. The use of forest biomass often results in a 'carbon debt', mainly because trees take decades or even centuries to reabsorb the emitted CO_2. Transporting and processing biomass feedstocks requires energy, which is often derived from fossil fuels. This increases the overall carbon footprint. Cultivating energy crops on land previously used for forests or grasslands may lead to land-use changes, which releases significant amounts of carbon stored in soils and vegetation. The decomposition of organic matter in storage or waste streams can release methane (CH_4), a potent greenhouse gas. The fertilizers used in energy crops can emit nitrous oxide (N_2O), further contributing to greenhouse gas emissions.

While some biomass energy systems are carbon-intensive, especially when poorly managed, sustainable practices and innovative technologies can make biomass a viable component of net-zero strategies. The BECCS, in particular, holds great promise for carbon-negative outcomes, helping offset emissions from harder-to-decarbonize sectors like aviation and heavy industry. To achieve net-zero emissions with biomass, a balanced approach that integrates sustainable practices, advanced technologies, and carbon removal systems is essential.

5.7 Innovation in tidal energy

Recent technological innovations have rapidly transformed the global tidal energy sector. AI-based predictive maintenance systems have improved reliability because they identify potential failures before they occur, thus reducing downtime and maintenance costs. Modular turbine designs allow easier installation, scaling, and maintenance in various marine environments. Hybrid systems combining tidal energy with other renewable sources such as solar or wind provide greater energy stability and efficiency, addressing the issues of intermittency and grid integration. Advanced monitoring programs that utilize AI sensors and satellite data from manufacturers like Planet or Maxar (Edwards et al., 2022; Ukoba et al., 2024) can further enhance operational efficiency and environmental monitoring.

While tidal energy offers unique benefits such as predictability and long operational lifespans, it faces significant barriers in terms of scaling. Factors such as initial capital costs, complex permitting processes, and a limited number of suitable sites constrain expansion. Compared to wind and solar energy, which have witnessed dramatic cost reductions and rapid deployment, tidal energy lags due to its reliance on specialized infrastructure and nascent technologies. Overcoming these challenges will require technological innovation and coordinated policy support.

The tidal energy sector may benefit from analyzing the approaches adopted in other industries. Offshore wind has demonstrated effective methods for cost reduction and large-scale deployment. The oil and gas sector offers expertise in subsea engineering and robust infrastructure design, whereas floating solar systems provide insights into innovative anchoring and modularity. Incorporating these practices can accelerate tidal energy development and subsequently improve efficiency.

Multiple tidal energy projects in a single region can exacerbate environmental impacts, such as habitat fragmentation and changes in water dynamics. Such cumulative effects facilitate the need for coordinated regional planning and adaptive management strategies. Comprehensive monitoring programs that integrate advanced sensors and AI tools can help track ecological changes and inform mitigation measures over the lifespan of the projects. Frameworks for community engagement, such as Scotland's community wind schemes (The Scottish Government, 2019), offer valuable models for developing communication strategies and building public support.

5.8 Financing and regulatory hurdles

Regulatory hurdles are among the most significant challenges for tidal energy development. Factors such as lengthy permitting processes, inconsistent government support, and public concerns surrounding ecological impacts often delay or derail projects. Clear, streamlined policies and stronger incentives for renewable energy adoption can help overcome these barriers. Enhanced public engagement can also help build support for tidal projects. The development of tidal energy facilities requires a comprehensive understanding of various regulatory frameworks to ensure environmental protection, legal compliance, and successful project implementation. The Maine Department of Environmental Protection (2018) provides an overview of tidal and wave energy technologies, elucidating the regulatory processes governing such projects in this region and thus emphasizing environmental standards and permitting requirements. The Acadia Tidal Energy (n.d.) discusses the interplay between provincial and federal regulations in Canada related to tidal energy development, which highlights the jurisdictional roles and environmental considerations. Johnson and Jansujwicz (2015) explores the concerns of regulatory and resource agencies regarding the installation of tidal energy structures, and it mainly focuses on the impacts on water flow and tidal regimes. Lange et al. (2018) examined the governance challenges and regulatory frameworks that affect marine renewable energy developments in the United States, offering insights into policy and decision-making processes. These resources offer an introduction to the regulatory considerations essential for the development and implementation of tidal energy projects. However, this is beyond the scope of this work.

Tidal energy systems currently possess higher capital and operational costs compared to other renewables. Detailed cost analysis, including LCOE, is essential to quantify economic feasibility. LCOE accounts for the total lifecycle costs of a project, including construction, operation, and decommissioning, divided by the total energy produced. Understanding these metrics can guide investments and policy decisions.

Innovative financing models are crucial for funding tidal energy projects, given their high upfront costs. Green bonds, which attract investors who are interested in environmentally sustainable projects and public–private partnerships, can provide the necessary capital. Community-based investment schemes can also enhance public support while diversifying funding sources. The successful implementation of green bonds in renewable energy financing, such as those used by Orsted for offshore wind (Ørsted, n.d.), demonstrates the feasibility of this approach.

Tidal energy faces challenges such as intermittency, which affects energy availability, and dispatchability, which is the ability to supply energy on demand. Grid integration remains a significant issue due to the remote locations of many tidal energy sites. Advanced energy storage systems and improved grid infrastructure may help overcome these challenges.

Several high-profile tidal energy projects have faced some critical setbacks, providing valuable lessons. The La Rance plant, while successful, revealed the significance of long-term maintenance planning. OpenHydro, an ambitious tidal turbine project, failed due to financial mismanagement and technological hurdles. The Swansea Bay Lagoon project in the UK was halted mainly due to concerns over cost-effectiveness, which highlights the need for robust economic planning.

Advanced tools and methodologies are enhancing tidal energy analysis. The integration of AI could improve predictive maintenance and resource forecasting, reducing operational risks and costs. Lifecycle assessments help evaluate the environmental and economic impacts of projects from inception to decommissioning. Experience curves, which analyze how costs decrease with cumulative production, provide insights into potential cost reductions as the industry matures.

6 Limitations of this study and recommendations

This study is subject to several limitations, such as data availability, geographical focus, and methodological constraints. Limited access to proprietary industry data constrained the scope of economic analyses. While global in scope, detailed analyses were confined to regions with readily available data, primarily Europe and Asia–Pacific. The reliance on secondary data constrains the granularity of technical and environmental impact assessments.

Future research should address these limitations by incorporating primary data collection and expanding geographic and technological analyses.

Based on the findings, the following recommendations are suggested:

- Policy and Regulatory Support: Establish clear and stable policy frameworks to attract investment and streamline permitting processes.
- R&D Investment**:** Prioritize funding for advanced turbine designs, biofouling mitigation, and predictive maintenance technologies. This prioritization is justi-

fied by the potential of tidal energy to provide predictable baseload power, complement intermittent renewables, and address energy security concerns. This makes it a strategically important area for R&D investment, which is comparable to or exceeding the strategic importance of continued investment in solar R&D or energy efficiency.

- Public Engagement: Develop transparent communication strategies to address community concerns and enhance stakeholder support.
- Integrated Energy Systems: Explore synergies between tidal energy and other renewables, such as hybrid systems combining tidal and offshore wind energy.
- Cost Reduction Strategies: Leverage economies of scale and innovative financing mechanisms to improve economic competitiveness.

7 Conclusions

Tidal power is a promising yet underutilized source of renewable energy. It leverages the predictable rhythms of ocean tides to generate electricity. Although technologies such as tidal stream generators and tidal barrages are well-established, the sector faces critical challenges such as high initial costs, environmental concerns, and a limited number of suitable sites for large-scale implementation. Recent advancements in axial-flow turbine design and the emergence of tidal lagoons indicate a shift toward highly efficient and environmentally responsible approaches.

Tidal energy projects can significantly affect marine ecosystems. The installation of tidal turbines and supporting infrastructure may alter natural water flow patterns, and this may subsequently affect sediment transport and marine habitats. Altogether, these factors may lead to erosion, changes in nutrient distribution, and disturbances to marine life, including fish and migratory species. The noise pollution from construction and operational activities can disrupt sensitive species, while physical barriers created by turbines may increase the risk of collisions for marine animals. Additionally, the supply chain, from hardware production to decommissioning, generates carbon emissions and waste that must be efficiently managed to minimize ecological harm. Long-term monitoring and mitigation strategies are crucial to mitigate these issues.

Large-scale initiatives like the Rance and Sihwa Lake tidal power stations have demonstrated the feasibility of tidal energy. However, a broader adoption still depends on overcoming substantial economic and technical hurdles. Innovations in turbine technology and strategic site selection may alleviate some of these challenges. Furthermore, ocean current turbines and stream tidal turbines share many similarities, and their continued development could significantly enhance the prospects for marine energy.

The SAM serves as an essential tool for evaluating the performance and economic viability of tidal energy projects, provided it integrates accurate data from commercial turbines (data that are currently lacking) and undergoes proper validation. By integrating detailed resource information and array configurations, the SAM can assist developers and policymakers in estimating the LCOE, thus facilitating informed decisions regarding the deployment of tidal energy technologies.

Ultimately, while tidal energy holds significant potential, its future growth depends on factors such as ongoing research, development, and collaboration among stakeholders to enhance efficiency, lower costs, and mitigate environmental impacts. As technology advances and the demand for renewable energy solutions grows, tidal power could play a vital role in diversifying the global energy portfolio and contributing to climate change mitigation efforts. The term tidal energy 'Vital Role' is linked to quantified goals such as energy security, demand management, and carbon neutrality.

While tidal energy faces considerable challenges, its potential for use as a reliable, renewable power source makes it a vital component of the global energy transition. Ongoing advancements in technology, coupled with supportive policies and cross-sector collaboration, could help overcome existing barriers and unlock the full potential of tidal energy systems.

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Alberto Boretti. The first draft of the manuscript was written by Alberto Boretti and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

The data that support the findings of this study are available from https://sam.nrel.gov/download.html.

Declarations

Ethics approval and consent to participate

Not applicable. This article does not contain any studies with human participants.

Competing interests

The authors declare that they have no competing interests.

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