

# Wave and Tidal Energy Cost Reduction and Performance Improvement Opportunities

FINAL REPORT

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*Prepared exclusively for U.S. Department of Energy/Water Power Technologies Office*

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# 1 EXECUTIVE SUMMARY

This study explored cost reduction and performance improvement opportunities in marine energy technologies, specifically focusing on wave and tidal energy. Initially, a comprehensive literature review was conducted to determine the key drivers that have the largest impact on reducing levelized cost of energy and are achievable in the near-term. The top drivers for wave and tidal energy were identified as power; structural design and device profile; anchoring and mooring; operations and maintenance; and arrays. However, exploration of literature highlighted the scarcity of reliable data in the field, due to factors like the early stage of technology, limited deployments, and lack of transparency and information sharing by industry. Following the literature review, 13 subject matter experts from 5 national and international organizations were consulted to gain depth and breadth to findings from literature. Expert feedback confirmed the issue of insufficient data and highlighted the need for targeted funding for innovations with specific objectives, along with collaboration and sharing of knowledge and resources. They emphasized the need to address developers' overly optimistic data to reduce error margins and suggested focusing research on "known unknowns" and uncertainties for better planning and decision-making.

Based on insights from both literature and expert interviews, four approaches are recommended to advance marine energy technologies. The *consortium model* proposes a voluntary government-industry partnership to enable pre-competitive information sharing. *Technology validation* involves analyzing real-world data to validate technology performance under realistic conditions, providing both individualized and aggregated analysis results to partners. The *inverse levelized cost of energy (LCOE)* approach starts with a target LCOE and works backward to determine the maximum allowable cost for each component. Lastly, *funding innovations with specific objectives* emphasizes taking a holistic view of key drivers, ensuring robust design (increasing availability, survivability and reliability), and incremental technology development.

## 2 WHY THIS STUDY

Marine energy resource potential is vast, with significant opportunities in the United States (U.S.) and globally to help improve the affordability, reliability, resiliency, and security of the American energy system. However, deploying technology in the marine environment presents challenges, and marine energy technologies are at various stages of development, with a range of devices being explored. To establish a viable industry, research and development (R&D) must enhance performance and reduce costs of marine energy technologies to make them competitive with other renewables and ultimately allow them to contribute to grid-scale electricity or power off-grid applications.

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### Objective

Large-scale commercialization and grid-scale deployment of marine energy technologies requires significant LCOE reductions that are driven by performance improvements and cost reductions at the component level. However, the path forward to marine energy technology development is not fully

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clear. According to the University Marine Energy Research Community, industry developers and researchers are highly motivated to conduct R&D in the marine energy field, driven by the technical challenges they face (Hirsch, 2023). However, when they were asked about the clarity of the development path of marine energy, significant uncertainty remained. To clarify that path, this study conducted a rigorous, unbiased review of publicly available literature on marine energy technologies to identify the key drivers with most potential to reduce the LCOE and the cost reduction pathways that are achievable in the near term.

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## Scope and Methodology

The main categories of marine energy are wave, tidal (tidal range and tidal current), ocean current, ocean thermal energy conversion (OTEC), and salinity gradient energy. This study focused on devices powered by waves and tidal currents, as these two pathways have the most advanced development timeline among marine energy technologies. Figure 1 illustrates the study's methodology.

Approximately 140 publicly available resources were reviewed and evaluated to synthesize cost driver information. These included resources such as PRIMRE (Portal and Repository for Information on Marine Renewable Energy) (National Renewable Energy Laboratory, n.d.), national and international marine and energy organization websites and documents, documents cited in reports, and a broad internet search. Of the 140 resources reviewed, 25 provided information of value in some form for this research. These 25 resources were further explored to uncover key drivers with the largest impact on reducing LCOE. Descriptions of the main drivers impacting costs of wave and tidal current energy systems were in 15 of the 25 documents. However, only 9 of the 15 documents provided more granular information on the drivers; the remaining 6 only had generic mentions. Of the 15 documents with information on key drivers, only 3 presented quantitative values of the impact of the key drivers on LCOE.

A data table compiled information on the mentions of drivers, along with any quantitative values assigned to the impact of these drivers on LCOE. Since each reference used slightly different wording to describe the drivers, they were arranged under common wording and categories. The frequency of each mention of a driver was analyzed to determine the priority order of the drivers (as shown in section 4).

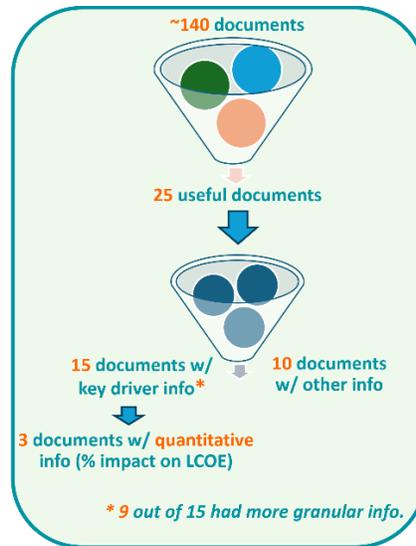


FIGURE 1. LITERATURE REVIEW METHODOLOGY

## Impact

Results are expected to inform future R&D by the Department of Energy Water Power Technologies Office (WPTO), leading to needed cost reductions and performance improvements to enable a viable commercial marine energy industry.

## 3 MARINE ENERGY

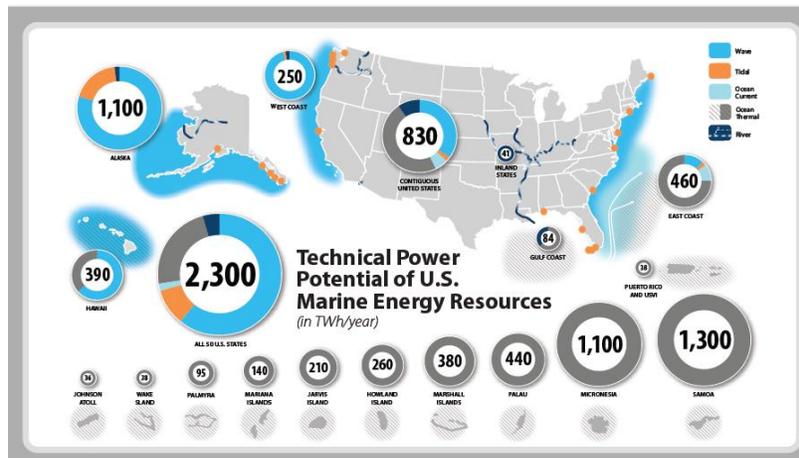
Marine energy involves extracting energy from oceans, seas, and rivers. Technologies are in different stages of development and are based on extracting energy from either the movement of the water (waves, tides, currents) or differences in temperature or salinity. In addition to the main marine energy categories (wave, tidal, ocean current, OTEC, and salinity gradient energy), hybrid approaches combining marine energy devices with offshore wind, floating offshore wind, and floating photovoltaic technologies are also being deployed on a small scale. These hybrid approaches can reduce costs by sharing facilities and maintenance while also maximizing and stabilizing energy output.

## Resource Potential and Deployments

Globally, ocean energy technologies have the theoretical potential to generate between 45,000 Terawatt hours (TWh) and over 130,000 TWh of electricity annually (IRENA, 2020). The most likely total is 76,350 TWh/year, with ocean thermal energy contributing the most (44,000 TWh/year), followed by wave energy (29,500 TWh/year), salinity gradient (1,650 TWh/year), and tidal current energy (1,200 TWh/year). In the United States, the total marine energy *technical* resource (portion of the theoretical potential that can be captured using existing technology options) is about 2,300 TWh/year (Kilcher et al., 2021). Wave resources make up 1,400 TWh of that total, and tidal resources make up 220 TWh. If the

Pacific and Caribbean territories and freely associated states are also considered, an additional 4,100 TWh/yr of ocean thermal energy resource is available. These marine energy resources are distributed throughout the country and its territories, as seen in Figure 2.

- *Wave energy* is abundant at the coastlines and is particularly energetic along the Pacific shorelines (California, Oregon, Washington, Alaska, and Hawaii).
- *Tidal energy* could play a major role in Alaska’s electricity generation and could also contribute to power in Washington State and several Atlantic states.
- *Ocean current energy* is mainly contained in the Gulf Stream and has the potential to provide power to North Carolina, South Carolina, Georgia, and Florida.
- *Ocean thermal energy* is a significant opportunity for parts of the Atlantic coast as well as the Gulf Coast states, Hawaii, and U.S. Pacific territories and freely associated states.
- *Riverine resource* can be harnessed for power throughout the country.



**FIGURE 2. TECHNICAL POTENTIAL OF MARINE ENERGY RESOURCES IN THE U.S. (KILCHER ET AL., 2021)**

Globally, the main regions and countries investing in wave and tidal energy projects are the United States, Europe, China, Korea, and Australia (only wave energy). Europe leads the industry, with 65 percent of tidal and 80 percent of wave developers based there (du Fornel et al., 2024).

## Benefits

Marine energy resources are abundant, geographically diverse, and energy dense. Tides are highly predictable, and waves are less uncertain than wind. In the near-to-medium term, marine energy can support blue economy applications, meaning that it can provide renewable power to systems such as desalination, aquaculture, underwater vehicle charging, and ocean observation/monitoring, enabling data collection and accelerating marine energy technology development. Marine energy’s predictability complements variable renewable energy resources such as solar and wind, enabling it to power large

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cities and coastal communities, as well as enhancing the resilience of remote and underserved communities through microgrids.

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## Challenges

Marine energy challenges fall into three main areas:

- *Operational environment.* The marine environment is challenging for technology deployment due to continuous water movement, salinity, strong winds, and precipitation. All components of marine energy systems need to be stress and corrosion resistant. For example, wave and tidal energy converters need to withstand both regular and extreme storm conditions. Wave energy converters face a bigger challenge, because they face a greater difference between normal and extreme loads than tidal energy converters do.
- *Infrastructure needs.* Electricity from tidal or wave resources is transmitted via seabed cables to onshore substations and then to the main utility grid or stored in a local battery system. The lack of sufficient infrastructure for energy storage and transmission further limits development. Installing and maintaining wave and tidal energy converters in the ocean is more time-consuming and costly than on land due to the need for specialized equipment, professional divers, and challenges posed by weather.
- *Environmental impacts.* Due to the nascent nature of marine energy technologies, their impact on the marine ecosystem is still being researched. Potential negative impacts could be seen related to habitat loss, noise, electromagnetic fields, and animal-device interactions. Increased vessel traffic for installation and maintenance can result in further environmental impacts. While some insights from the oil and gas and offshore wind sectors can be leveraged, impacts from marine technologies need further evaluation.

The challenging operational environment, infrastructure needs, and measures needed to reduce environmental impacts, along with the nascent nature of the energy conversion technologies, all lead to a higher cost of energy from marine resources. Whereas the LCOE of most other renewable energy technologies has come down to about \$0.03/kWh to \$0.12/kWh (IRENA, 2024), wave and tidal energy costs are about \$0.20/kWh to \$0.85/kWh (Baca et al., 2022; IRENA, 2021; ORE Catapult, 2024).

## 4 LITERATURE REVIEW FINDINGS

Wave and tidal energy technologies are in their early stages, with ongoing efforts to gather more detailed data and comprehensive insights. The projects deployed are valuable demonstrations but have not been operational long enough to generate substantial data. While project developers are working to accumulate enough experience to be able to share insights on key cost reduction drivers, most of the current relevant information comes from national and international research organizations, which base their estimates on a mix of available literature, modeling, and expert interviews. As a result, this literature review offers a mostly qualitative overview of potential cost reduction drivers, along with estimates of current and future LCOE values and timelines.

## Current LCOE & Future LCOE Targets

Three organizations have provided estimates of the current LCOE for wave and tidal current energy technologies (see Table 1).

**TABLE 1. CURRENT LCOE ESTIMATES FOR WAVE AND TIDAL CURRENT ENERGY**

REFERENCE	CURRENT LCOE ESTIMATE*	TECHNOLOGY
National Renewable Energy Laboratory (Baca et al., 2022)	\$0.43–\$1.05/kWh	Wave
International Renewable Energy Agency (2021)	\$0.38–\$0.69/kWh	Wave
International Renewable Energy Agency (2021)	\$0.25–\$0.57/kWh	Tidal Current
ORE Catapult (2024)	\$0.33/kWh	Tidal Current

\*The LCOE values found in literature were converted to Dollars (for those not reported in Dollars; using the exchange rate from the year reported) and also converted to constant Dollars using the Consumer Price Index to factor in the differences in reporting years.

These organizations also provided estimates for future LCOE values, indicating potential levels and expected timeframes for achieving them (see Table 2).

**TABLE 2. FUTURE LCOE ESTIMATES FOR WAVE AND TIDAL CURRENT ENERGY**

REFERENCE	FUTURE LCOE ESTIMATE	TARGET YEAR	TECHNOLOGY
International Renewable Energy Agency (2021)	\$0.22/kWh	2025	Wave
International Renewable Energy Agency (2021)	\$0.17/kWh	2030	Wave
International Renewable Energy Agency (2021)	\$0.11/kWh	early 2030s	Tidal Current
National Renewable Energy Laboratory (Baca et al., 2022)	\$0.30/kWh	2029–2033	Wave
National Renewable Energy Laboratory (Baca et al., 2022)	\$0.07–\$0.13/kWh	2050	Wave
ORE Catapult (2024)	\$0.06–\$0.14/kWh	2035	Tidal Current

Ocean Energy Systems (OES), the International Energy Agency (IEA) technology collaboration program for ocean energy, has a goal to reach 300 GW of ocean energy (180 GW wave and 120 GW tidal) by 2050 (Gordon et al., 2023). To meet this goal, IEA-OES estimated the financial investment needed to create a global market pull mechanism. They examined various levels of technology cost reduction and found that lower cost reductions require more investment for tidal or wave technologies to reach market parity. In some cases, even with larger investments, these technologies would not achieve market parity even by 2050. Table 3 presents these scenarios.

**TABLE 3. COST REDUCTION SCENARIOS AND MARKET PARITY FOR WAVE AND TIDAL CURRENT ENERGY**

COST REDUCTION SCENARIO	DATE MARKET PARITY REACHED	INVESTMENT NEEDED	TECHNOLOGY
Optimal Cost Reduction (15%)	Mid 2040s	\$56 billion	Tidal Current
Optimal Cost Reduction (15%)	Mid 2040s	\$74 billion	Wave
Moderate Cost Reduction (12.5%)	Late 2040s	\$132 billion	Tidal Current
Moderate Cost Reduction (12.5%)	Late 2040s	\$170 billion	Wave
Suboptimal Cost Reduction (10%)	2050 (but market parity not reached)	\$275 billion	Tidal Current
Suboptimal Cost Reduction (10%)	2050 (but market parity not reached)	\$378 billion	Wave

### Cost Breakdown Structure

The U.S. Department of Energy (DOE) created a standardized framework—a cost breakdown structure (CBS)—for collecting and reporting all cost and performance data for marine energy technologies, including capital expenditures (CapEx) and annual operating and maintenance expenditures (OpEx) (Neary et al., 2014). The CBS itemizes all project lifetime expenses such as design, permitting, equipment purchases, operations and maintenance (O&M), and decommissioning and has six levels. Level zero is the main project, and all other cost levels stem from it. Level 1 is very general, and each subsequent level becomes more specific. CapEx includes costs for activities before starting marine energy operations. OpEx includes costs for operating and maintaining the marine system, including ongoing environmental monitoring.

The CBS was designed to be broad enough to accommodate cost data from a variety of marine energy technologies, while still allowing for detailed customization for specific devices. So, the more detailed levels of the CBS (especially levels 4 and 5) may contain elements that are device specific. For example, for power conversion chain costs (level 3), level 4 costs could include: generator, drivetrain, converter, gearbox and driveshaft, hydraulic system, step-up transformer, energy storage, etc. At this level of detail, cost categories are expected to vary across technologies and even across devices within the same technology. Figure 3 shows DOE’s full CBS down to the third level.

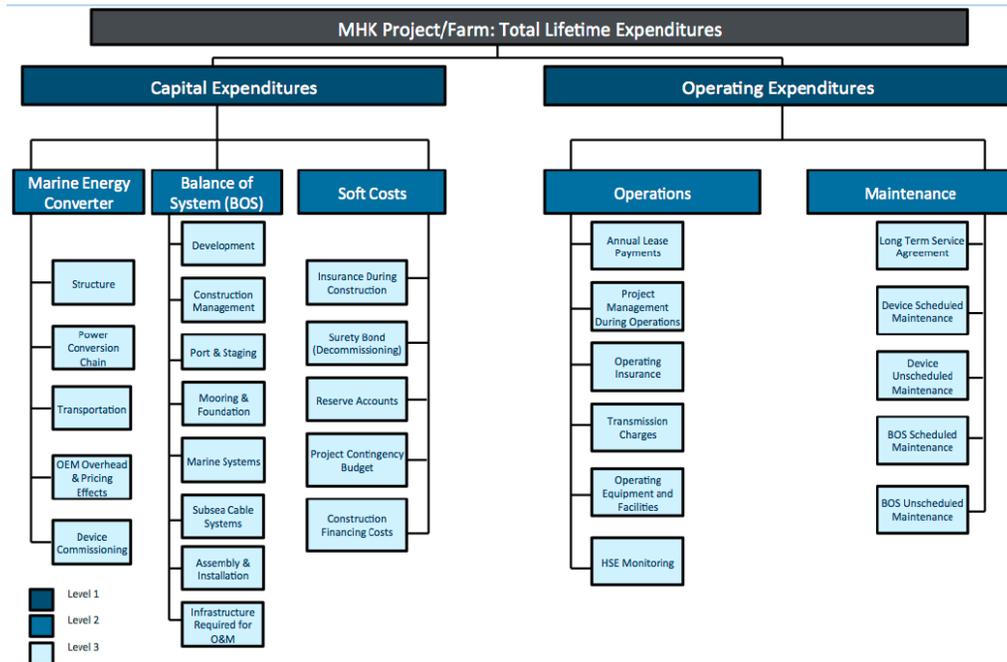


FIGURE 3. COST BREAKDOWN STRUCTURE FOR MARINE ENERGY TECHNOLOGIES

## Key Cost Reduction Drivers & Impact on LCOE

The overall LCOE of marine energy technologies is based mainly on capital costs, O&M costs, and the amount of electricity produced (performance). There is no fuel cost since marine energy is free at the source. Decommissioning costs at a project's end-of-life are expected to be minimal compared to its capital costs, and when discounted to the present value, would have a minor impact on the cost of energy. Capital costs are impacted by the cost of the marine energy device (material, components, labor), installation costs, foundations and moorings to keep the device in place, and cables and other components to connect it to the grid. O&M costs mainly relate to maintenance (planned, unplanned, overhaul during service life if more feasible), licenses, insurance, and ongoing monitoring. All of these costs eventually depend on both the size of the installation and the deployment location. O&M costs are harder to estimate than capital costs due to limited operational experience, but some related costs can be inferred from offshore wind and oil/gas sectors.

The top five drivers identified from literature for both wave and tidal current energy technologies were:

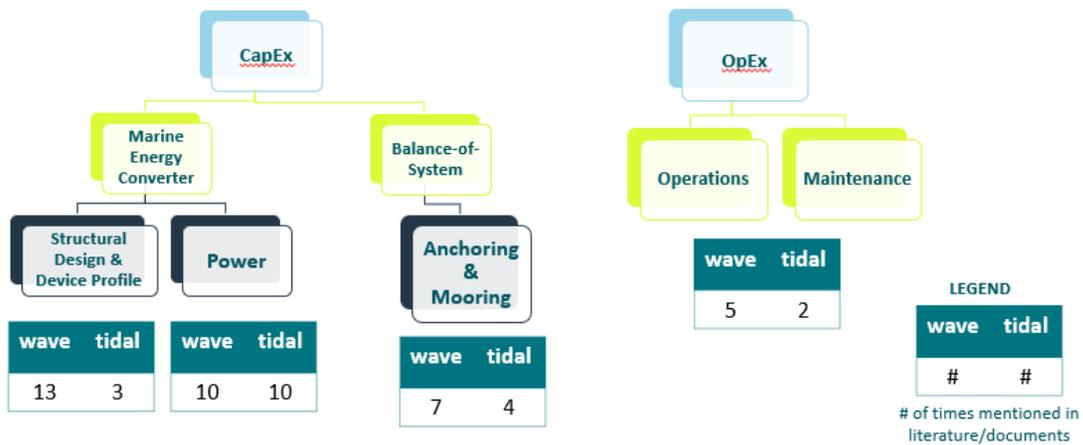
1. Power
2. Structural design and device profile
3. Anchoring and mooring
4. O&M
5. Arrays

Wave and tidal current energy prioritized these five drivers slightly differently (Table 4).

**TABLE 4: RANKINGS OF THE TOP FIVE DRIVERS FOR EACH TYPE OF MARINE ENERGY, IN DESCENDING ORDER OF IMPORTANCE**

PRIORITY ORDER	WAVE ENERGY DRIVERS	TIDAL CURRENT ENERGY DRIVERS
1	Structural Design and Device Profile	Power
2	Power	Structural Design
3	Anchoring and Mooring	Anchoring and Mooring
4	Operations and Maintenance	Arrays
5	Arrays	

The frequency of mentions in literature for these drivers can also be shown in relation to the CBS structure, as illustrated in Figure 4.



**FIGURE 4. KEY DRIVERS' RELATIONSHIP TO THE CBS AND FREQUENCY OF MENTIONS IN LITERATURE**

The following subsections discuss the drivers for wave and tidal current energy. In each subsection, the drivers are discussed in their order of importance to that energy type.

## WAVE ENERGY

### KEY DRIVER: Structural Design and Device Profile

Wave energy conversion devices are structurally defined by two key aspects: the physical structure and the device profile.

- The physical structure is the largest contributor to capital costs and must withstand both the cyclic pressure loading from the waves and tension loading from the mooring line connection points.
- The profile of the device relates to its size and shape, which depends on power conversion requirements.

Optimizing a wave energy conversion device's profile and/or physical structure can reduce LCOE. If a device's profile is optimized, its energy capture is increased, leading to lower LCOE. Especially in

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attenuator wave devices, the device's length influences the amount of energy captured. Optimizing the structural design of wave energy devices aims to reduce excess margin in factors of safety<sup>1</sup> while maintaining performance. The main goal is to understand the loads acting on the structure, as well as factors like manufacturing, transportation, and material usage. Understanding the loads on a wave energy device, especially during extreme weather, is crucial for its survivability. These events can cause dynamic nonlinear loading, such as pressure, water on deck, and impacts on un-submerged sections. Moreover, optimizing the type and quantity of materials in the structure can reduce capital and maintenance costs while still meeting design and performance criteria.

### **KEY DRIVER: Power**

Every step of the power conversion chain (PCC) in a wave energy converter results in high energy losses, reducing efficiency. However, these losses present an opportunity to improve efficiency at various points in the chain. The PCC is also a major contributor to capital expenditure. Thus, the design aspects of a PCC are important in reducing LCOE.

- Integrating the drivetrain with the generator or optimizing single-rotation generators for the variable-rate drivetrains of wave energy converters can both enhance efficiency.
- The size and cost of each PCC component are determined by the loads on it during survival conditions. Therefore, removing the PCC from the load pathway or reducing the impact of large loads can help lower costs.
- Sizing PCC components also depends on system efficiency, converted power, and storage needs, all of which must be carefully considered. Given the high cost and weight of onboard storage, minimizing the required storage capacity is beneficial.
- Systems-level modeling can identify which PCC components need customization and which can be off-the-shelf.

### **KEY DRIVER: Anchoring and Mooring**

Designing mooring is challenging because it must limit device movement while allowing efficient power extraction and orientation towards favorable wave directions. The wave energy sector currently relies on practices, materials, and factors of safety from the oil and gas industry in developing mooring for wave energy devices. However, the deployment locations and operational conditions of wave energy devices are quite different than that of the oil and gas industry. For example, wave energy devices are unmanned (vs. manned), are moored in much shallower water (vs. deeper), and are designed to have large oscillation amplitudes (vs. motionless).

Mooring designs must meet both operational and survival requirements under extreme conditions, while also maintaining a specific footprint. The high ratio between design and operational loads significantly impacts capital and operational costs. Alterations to the mooring design can affect capital costs (including the mooring system and wave energy device structure), mooring deployment costs, mooring maintenance schedules, wave energy device maintenance costs, and acceptable deployment

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<sup>1</sup> Factors of safety (or safety factors) are applied to wave energy device components to accommodate extreme conditions and irregular loading. They indicate how much stronger the system is than necessary for the intended load, essentially how much it is over-built.

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locations. Designing mooring systems should also consider factors such as the dynamics of mooring lines within the water column, deployment depths, and material limitations.

Novel designs should focus on reducing the mooring system footprint while finding ways to absorb loads at locations other than the wave energy converter attachment points. Improving mooring design will involve evaluating and testing new materials that are resilient in the marine environment and can withstand large loads.

Mooring systems for wave energy devices typically are designed independently from the wave energy converter. However, design can further be improved by integrating active mooring systems with the wave energy converter's control system for power extraction, reducing loads on the wave energy device and providing storm protection.

#### **KEY DRIVER: Operations and Maintenance**

Any maintenance requires some downtime for the wave energy device, impacting availability and raising the cost of wave energy. If maintenance events happen during timeframes that are planned and scheduled beforehand, maintenance costs could be reduced. Maintenance can be scheduled according to the predicted failure rates of components and for refurbishment at the half-life of the device. Scheduling timeframes also depend on factors such as favorable weather windows, distance from port, vessel needs, and availability of replacement parts. The weather window cutoff, often dependent on vessel size, significantly impacts device LCOE.

The impact of maintenance on wave energy device availability and costs can be minimized by arranging maintenance for forecasted periods of low energy availability, if possible. Moreover, the design of wave energy devices should fully integrate not only maintenance but also deployment and recovery. Such a design would include common or plug-and-play components, easy access to high-priority sections, enhanced locking/unlocking mechanisms, and standardized vessel attachment points.

#### **KEY DRIVER: Arrays**

Placing several wave energy devices close together in an optimized array can generate more energy and reduce the system LCOE. This optimization uses as few devices and anchors as possible while still achieving the targeted energy level. The array layout not only defines the total power output but also impacts the power performance of each device individually. This, in turn, affects capital costs, particularly in areas such as environmental permitting, infrastructure, installation, maintenance, and mooring. Optimization goals include minimizing environmental impacts and enhancing performance (power delivery, energy storage, reduced power fluctuations), infrastructure (large arrays vs. clusters of smaller arrays, substations needed), and installation. Additionally, minimizing the array's footprint allows shared mooring and anchoring, potentially reducing related costs.

## **TIDAL CURRENT ENERGY**

#### **KEY DRIVER: Power**

Increasing the rotor diameter of a tidal current turbine captures more energy from the resource, similar to how wind turbines operate. Installing larger turbines is feasible to a certain extent, as rotors need clearance from the seabed for fixed devices and from the sea surface for floating devices to avoid navigational hazards. Analyses have shown that increasing the rotor diameter of a tidal current turbine can increase the energy capture per turbine by over 40 percent (Frost, 2022b), reducing the overall LCOE

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by 20 to 24 percent (Frost, 2022b; ORE Catapult, 2024). The benefits of increased energy capture, however, must be weighed against related costs such as manufacturing, transport, installation, and design changes to accommodate larger mechanical loads. Increasing the rated power of a turbine can also increase its energy capture. Analyses have shown that an increase in rated power can decrease the overall LCOE by about 5 to 10 percent (ORE Catapult, 2024).

Considering the rotor diameter and rated power together is beneficial, as an optimal combination of these two factors maximizes energy production for a given flow speed. However, due to limited device deployments, these optimizations have not yet been seen in practice. Developers will initially aim for the largest possible rotor diameter, to take advantage of cost scaling and performance benefits. Further analysis shows that the combination of increased swept area and generation capacity reduces LCOE much more than either factor alone, up to 37.7 percent (Frost, 2022b).

The power takeoff (PTO) system of a tidal current turbine also plays a key role. It converts the mechanical energy of the rotor into electrical energy, and any losses in efficiency or failure of the PTO impact the amount of power generated, as well as other turbine components. Thus, improving both the efficiency and the reliability of the PTO system is important. Gearboxes are a major component of the PTO system but are prone to failure, which increases O&M costs. PTO systems can be direct-drive, without a gearbox, with the rotor shaft directly attached to the generator. But these systems require high-torque, low-speed generators, which are more costly due to the enhanced controls and magnets needed.

#### **KEY DRIVER: Structural Design**

Optimizing a tidal turbine's structural design increases the amount of energy it captures (power-to-weight ratio). Such an optimization is a key pathway to LCOE reduction, as it involves both capital and operational expenses. Better load predictions and a maintenance-focused design can aid in optimizing the tidal current turbine structural design. Optimization enhances performance and minimizes unnecessary safety margins. Lightweight materials can complement the structural design optimization by further improving power-to-weight ratios and positively impacting deployment and maintenance. The platform for the turbines can also be optimized, impacting factors such as turbine serviceability, performance, and loading. Moreover, multi-use platforms could share infrastructure with desalination plants or marine aquaculture or serve as a breakwater.

#### **KEY DRIVER: Anchoring and Mooring**

Tidal current turbines generally use gravity-based foundations, which require significant amounts of steel. These large, heavy foundations need large, expensive vessels to transport them to the tidal site, increasing installation costs. Switching to monopile foundations could reduce system LCOE by 3.4 to 10 percent (Frost, 2022b), and tidal current turbines are expected to transition from gravity-based to piled foundations.

In the offshore wind sector, monopile foundations are common, as they are easier to manufacture and transport. Jacket foundations (composed of smaller pin piles) are also common in deeper waters. However, piled foundations have not yet gained as much traction with tidal current technology, as tidal sites tend to be rocky and require more drilling, adding to installation time and costs. Moreover, installation vessels (e.g., heavy-lift vessels and jack-up barges) capable of piling fixed tidal current turbine foundations are currently being oversized. But piled foundations could help reduce the overall LCOE by decreasing required materials by 90 percent, allowing more foundations to be transported per

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vessel. Despite potential cost increases related to development, installation, and decommissioning, significant savings from using less materials leads to an overall lower LCOE. Moreover, as the length and thickness of the piles depend on the turbine type and tidal resource site, further reductions in LCOE (up to 50 percent) could be seen (Frost, 2022b).

Future designs are likely to use smaller piles. And as both the offshore wind and tidal sectors grow, economies of scale can drive the cost of piled foundations down. Improvements in LCOE are also expected for floating devices that transition from gravity anchors to piled anchors, although to a lesser extent (due to mooring line and connector costs).

### **KEY DRIVER: Arrays**

Several turbines in an array layout capture more energy from a tidal stream. As array size increases, production costs per unit decrease, fixed costs are spread over more devices, and components can be standardized. However, to reduce the system LCOE, the spacing and orientation of the turbines in the array should be optimized. Optimizations involve turbine placement strategies to increase energy yield, manage blockage effects, minimize cabling, and reduce O&M through improved load prediction. These optimizations also consider factors such as structural loads, environmental factors, and energy storage.

Due to the limited deployment of full arrays and the site-specific nature of tidal current energy, high-fidelity modeling is needed to determine optimal array layouts. Parallels with the wind sector, like wake physics and turbine parameters, aid modeling efforts, but they don't fully address the complexities of tidal stream turbine mechanics and the environment they operate in. For example, tidal models need to consider a range of turbine diameters at different water depths, along with the impact of wave activity.

Various studies have shown that increasing the size of and optimizing tidal arrays can reduce LCOE by 10 to 28 percent. Nova Innovation's EnFAIT project in the Shetland Island of Scotland demonstrated even greater reductions. From 2017 to 2023, data collected as the initial three turbines were expanded to six and different array layouts were tested showed a 40 percent reduction in LCOE through optimized array layout (ORE Catapult, 2024; Frazer-Nash Consultancy, 2023).

## **5 INSIGHTS FROM EXPERTS**

This study aimed to gather, organize, and analyze detailed data on key cost reduction and performance improvement drivers for marine energy technologies. However, the comprehensive literature review revealed a lack of information. Therefore, this stage of the study sought feedback and validation from experts in the field to add depth to identified drivers, discover additional drivers, and quantify more of them to the extent possible. Detailed interviews were conducted with 13 marine energy experts from 5 national and international organizations. Their feedback confirmed the issue of insufficient data and provided additional insights into the challenges and strategies for advancing research.

### **Lack of Reliable Data**

Obtaining reliable information on cost reduction drivers for marine energy technologies is challenging due to the early stage of marine energy technologies and the proprietary nature of much of the data. The sector has over-promised and under-delivered, leading to difficulties in finding reliable literature, and much of the existing literature is theoretical and lacks real-world data. Due to the limited number of

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commercial-scale deployments, most data in the literature are also speculative or based on projections from related industries. For example, the International Electrotechnical Commission standard, which originates from the wind energy sector, does not translate well to marine energy. As a result, drivetrain and PTO design have deviated from the intended path. Moreover, the reasons for failures are not well understood, as the focus remains on other industries, leading us astray and slowing down progress. Due to a lack of experience and related data, estimates often differ from the actual outcomes of built projects. And many of the published documents are rooted in older analyses and data sets, which may not reflect current realities. Recent expert elicitation studies have shown more conservative estimates compared to what's found in literature, indicating a potential optimism bias in published reports.

## Levelized Cost of Energy

Accurately projecting the LCOE for new technologies is challenging, due to the lack of real-world data and the reliance on optimistic performance projections. It is crucial to obtain real-world numbers by deploying devices in the water to gather accurate performance and cost data, as without this, any estimates would be speculative and potentially misleading. Thus, current LCOE efforts might be premature, and more information about devices is needed before making cost predictions. New technologies generally take at least 30 years to transition from concept to commercial product, with cost considerations becoming significant in the final 10 years. But wave energy technologies have only been under development for approximately 5-8 years, while tidal energy technologies have been in progress for around 12 years. The absence of long-term deployments means that assumptions about O&M and project lifespan remain unvalidated. For instance, the Horns Rev Wind Farm experienced a steep learning curve during its initial commercial deployment, with the Danish government having to replace every gearbox within four years. This example highlights the challenges in validating LCOE projections for new technologies. Moreover, for marine energy, the different designs and lack of technological convergence make it hard to assign quantitative values to LCOE, making accurate projections difficult.

## Wave Energy

Wave energy devices require a shift in design philosophy. These oscillating systems are fundamentally different from other systems, and cost reduction drivers are interconnected due to bi-directional flow. This leads to a unique design process characterized by highly fluctuating power. Additionally, engineering and parametric estimates for similar designs cannot be applied to wave energy devices because of their unique designs, and there is no suitable software tool available due to the lack of experience.

The cost reduction pathways for wave energy are difficult to define due to the diversity of device types. Optimizing cost drivers for one type of device may not apply to another, making it hard to generalize cost reduction strategies. And new technologies keep emerging, indicating that no single technology has proven to be the best solution yet.

One of the inherent challenges in wave energy is the harsh marine environment. Devices must withstand high forces and corrosive conditions, which complicates the scaling of technologies and contributes to the slow progress in achieving cost-effective solutions. The high capital expenditure costs of wave devices, which need to be robust enough to survive harsh marine conditions, add to the overall expense of wave energy projects. Furthermore, wave energy devices need to be well-tuned to the specific wave conditions at different deployment sites, adding another layer of complexity.

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Despite these challenges, there is still optimism about the potential of wave energy. The energy density and continuous availability of waves are key advantages and finding markets where wave energy can be successful is crucial. Smaller, intermediary scales could provide valuable insights and opportunities for technological development. However, raising private finance for wave energy projects remains difficult, as the sector is perceived as risky and underdeveloped. Additionally, wave devices often underdeliver energy, producing less than their rated capacity due to the variability of wave conditions.

### RELIABILITY AND CONTROL SYSTEMS

Improving performance and reducing costs in wave energy systems hinge on reliability and control. These systems need to operate reliably for many years, enduring millions of cycles annually. Effective control systems are crucial for managing power and often prove more important than efficiency. For efficient energy harvesting, wave energy converters need to achieve resonance, but it must be carefully controlled to prevent damage to the device. Control systems are key for optimizing the power takeoff and maintaining resonance without causing harm. Integrating controls with power takeoff design can significantly improve performance, potentially increasing power conversion efficiency by 200% - 300%, and thus reducing costs.

### CO-DESIGN AND INTEGRATION

Co-design and integration are important for wave energy projects to ensure compatibility between different technologies and reduce costs. By bringing technologies together from the start, co-design can avoid incompatibility, reduce waste, and focus on promising solutions. Although research is funded in co-design, the literature does not explicitly discuss its potential for cost reduction. The assumption is that co-design improves the starting point for optimization and cost reduction.

## Tidal Energy

Tidal energy is easier to manage due to some convergence in technology, unlike wave energy. Tidal energy also offers better resource access, which is important for O&M. Turbines used to capture tidal energy can be any size, adding flexibility, whereas in wave energy, some concepts don't work when the device is smaller.

## KEY DRIVER: Structural Design

### WAVE ENERGY

Optimizing wave energy devices presents significant challenges due to the need for large structures that can effectively interact with waves. These structures are often difficult to design and manufacture. Therefore, it is essential to strike a balance between optimal design and manufacturability. While the ideal designs may be identified, they are often impractical to manufacture. Using standard materials and dimensions can help reduce costs, even if it means slightly compromising on the optimal design. Bespoke dimensions tend to be more expensive to source and manufacture. The majority of structural design is driven by loads, and a wave device essentially functions as a "floating PTO," meaning its design is closely tied to power and control strategy.

### TIDAL ENERGY

The current priority is to develop a reliable system that integrates power, structure, and other elements.

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While literature assumes functionality, focus should be on creating machines that work. Current designs prioritize robustness over optimization.

Tidal turbines should be designed with both installation and maintenance in mind to reduce costs and improve efficiency. The site of the turbine also affects structural optimization, so it is important to consider site-specific conditions and choose locations with less extreme environments. Using a single foundation for multiple turbines can save costs, as losing one or two turbines will not significantly impact overall performance. However, maintaining multi-turbine designs is challenging and costly, as the entire structure must be recovered to replace a single turbine.

Understanding loads is crucial for optimizing structural design and reducing costs. While fluid structure interaction tools are available, they are computationally expensive and not widely used in practice. Instead of conducting high-fidelity modeling, it is better to add a bigger safety factor and refine later. Modeling should be industry-wide and informed by actual deployments. Every wave and tidal system built so far is a prototype, not commercial. So, it is preferable now to have a system that is heavy and expensive and survives, rather than an optimized one.

## KEY DRIVER: Power

### WAVE ENERGY

It is crucial to address efficiency losses in the power conversion chain because fluctuating power significantly impacts overall efficiency. Optimizing PTO configurations for wave energy devices is challenging due to their varied design. This optimization is particularly important because power is the area that would benefit most from the convergence of device types. However, fluctuating power is problematic, as most systems, including power electronics and hydraulic systems, are designed for steady operation, which reduces efficiency. More research is needed to optimize PTO configurations. There is also a lack of off-the-shelf hardware designed for underwater use. While manufacturers can produce such hardware, without an established market, they are reluctant to do so. This makes further optimizing wave energy devices even more difficult, as the necessary components are not readily available.

### TIDAL ENERGY

Optimizing tidal blades is crucial for enhancing energy production. The focus should be on energy produced, rather than rated power. By derating machines, we can increase the capacity factor, which means producing more energy without increasing the rated power. This approach avoids the need for additional cables and expensive power electronics. The goal is to have the largest feasible rotor and derate the machine to achieve higher energy production with less rated power.

Optimizing the design of blades is key for improving performance. This includes using longer blades and different materials. Blades must handle various loads, and designs with trimming capabilities or torsional twisting can help shed loads effectively. While the tidal sector has largely adopted three-bladed horizontal axis designs, there are also vertical blade designs and innovative approaches like kite designs that offer different optimization strategies. Moreover, reducing the cut-in speeds of turbines allows them to operate in less vigorous resources, opening up new deployment opportunities in shallower areas.

## KEY DRIVER: Anchoring and Mooring

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## PRIORITIES

It is too early to be thinking about advanced anchoring and mooring solutions like piled foundations. Most developers are currently concentrating on prioritizing the reliability and performance of marine energy devices themselves. They are trying to de-risk prototypes by using known anchoring and mooring solutions. Their focus is on other areas of cost reduction, making anchoring and mooring less of a priority for optimization as a driver of cost reduction at this stage.

## DESIGN AND DEPLOYMENT CHALLENGES

Deeper waters increase anchoring and mooring costs due to the need for longer and more robust mooring systems. These solutions are often site-specific and vendor-specific, adding complexity to the optimization process. Especially in wave energy, anchoring and mooring are considered part of the device cost, highlighting their importance in the overall cost structure. Shared moorings could help reduce costs by allowing multiple devices to share a single mooring system. However, moorings often break during testing in dynamic marine environments, necessitating materials that can withstand harsh conditions. Current standards from the oil and gas industry may not be sufficient for marine energy applications. Additionally, near-term deployments are expected to incur higher costs for materials and installation due to a shortage of local vessels.

## FLOATING VS. BOTTOM-MOUNTED SYSTEMS

Floating systems are more cost-effective than bottom-mounted systems because buoyancy is cheaper than mass for resisting the forces exerted by currents. Thus, floating designs are becoming more common in the marine industry due to their cost-effectiveness and the ability to withstand dynamic water environments.

## KEY DRIVER: Operations and Maintenance

### WAVE ENERGY

It is important to minimize maintenance in wave energy devices, as maintenance activities in the ocean are expensive and challenging. And locations with the best wave resources have the fewest good days or weather windows for maintenance. To the extent possible, maintenance activities should be scheduled during periods of calm weather to reduce risks and costs. This is where array size becomes important, because maintaining multiple devices is significantly more challenging than maintaining a single device; more devices can lead to a maintenance nightmare.

### TIDAL ENERGY

Some tidal turbines have demonstrated good resilience and survivability by operating for five years without interruption. However, maintaining turbines in harsh environments remains challenging. Some device designs enable quick and efficient maintenance using smaller vessels, avoiding major recovery operations.

## KEY DRIVER: Arrays

Developers are currently focusing on other areas of cost reduction, making arrays less of a priority for optimization as a driver of cost reduction at this stage. Arrays are not necessarily seen as an innovation pathway; they are considered “baked in” when thinking about cost components, as a certain size array is assumed. Arrays mainly relate to achieving economies of scale.

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The size of an array is influenced by fixed costs, such as permitting, which will be incurred regardless of the array's size. Therefore, developers need to reach a certain size array to amortize these costs. Cost drivers for arrays include both the devices and the interconnections and substations, which helps in understanding the broader scope of cost considerations in array setups.

### WAVE ENERGY

There is potential for optimizing array layout for wave energy converters, including the spacing of devices and the impact on power capture, but this is a longer-term research area.

### TIDAL ENERGY

Optimizing array design to manage blockage effects is essential, but the lack of in-field data to validate models presents a significant challenge. The number of tidal conversion devices varies based on the site, making each situation unique and necessitating further research. The impact of blockage effects also varies by location, complicating the generalization of findings across different sites. While there have been some studies on blockage effects, they are still in the early stages and primarily academic, with limited practical applications so far. This early-stage research on blockage effects is similar to previous wind research on array effects and wake optimization.

## Infrastructure

Developing infrastructure for wave and tidal energy is challenging due to high costs of subsea cables and environmental impact assessments. The cost of purchasing and installing subsea cables is significant, with long lead times, and is a major capital driver for marine energy projects. These costs and lead times are not well-documented due to limited commercial-scale deployments, making reliable data scarce. If the offshore wind industry solves the cable problem first, the marine energy industry can then address it. Additionally, environmental monitoring is costly, especially in areas with endangered species, requiring continuous observation of the interactions between turbines and marine mammals using cameras and hydrophones. Automated solutions are needed to reduce the burden on operators, as continuous manual monitoring is unrealistic and expensive.

## Insurance and Risk Assessment

In nascent industries, there are public-facing Securities and Exchange Commission rules to publish risk profiles (e.g., coal industry and carbon capture), but not for marine energy. Collecting detailed data is important for the insurance sector to develop commercial insurance products for tidal and wave energy technologies. To feel confident in the technology, the insurance sector requires at least two years of uninterrupted data. However, in the marine energy industry, there aren't enough failure mode analyses. Project risk assessments can help the insurance sector understand the risks and costs associated with tidal and wave energy projects.

## Small and Medium Enterprises

Small- and medium-enterprises in the marine energy sector face challenges in developing sites, raising finance, and testing technology simultaneously, often with limited resources. Thus, they are often spread thin, trying to manage multiple aspects of their business with limited resources, making it difficult to focus on any one area effectively.

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## 6 CONCLUSIONS AND RECOMMENDATIONS

The comprehensive literature review and the detailed discussions with experts revealed that obtaining reliable information on cost reduction drivers for marine energy technologies is challenging due to their early stage, proprietary data, and reliance on projections from related industries, which leads to optimism bias and discrepancies between estimates and actual outcomes. Recent publications (last 3-4 years) have begun to include some quantitative values on the impact of these drivers, but only a few of them do so.

The key cost reduction identified drivers can also be mapped to the core activity areas of the WPTO, which are:

1. **Foundational R&D:** Focus on early-stage R&D for components, controls, manufacturing, and materials; validate numerical modeling tools; enhance resource assessments; and create metrics to evaluate device potential.
2. **Technology-Specific System Design and Validation:** Validate marine energy systems' performance and reliability through prototype and in-water testing for grid-scale, power at sea, and resilient coastal community markets.
3. **Reducing Barriers to Testing:** Provide access to various testing facilities and support environmental monitoring to understand risks and reduce costs.
4. **Data Access, Analytics, and Workforce Development:** Enhance access to data, tools, and STEM resources to raise awareness of marine energy advancements, streamline permitting, and develop a skilled workforce.

*Power, structural design, and anchoring/mooring* primarily pertain to the foundational R&D activity area. These drivers would benefit most from focused R&D in electronics, design, materials, and similar areas. On the other hand, *O&M* and *array optimization* are more aligned with system design and validation, as they address the overall system and its reliability.

Literature search and consultations with experts highlighted areas of research that could lead to potential LCOE reduction:

### POWER

**Literature:** Enhancing the power output of marine energy devices is an important driver for reducing LCOE. This involves optimizing the design and efficiency of the devices to capture more energy from the marine environment.

**Expert Views:** Optimizing tidal blades to enhance energy production involves using longer blades, different materials, and derating machines to increase capacity factor, focusing on energy produced rather than rated power, and considering various designs and cut-in speeds for broader deployment opportunities. Optimizing power take-off configurations for wave energy devices is challenging due to efficiency losses from fluctuating power and the lack of off-the-shelf underwater hardware, requiring more research and industry-wide solutions.

### STRUCTURAL DESIGN & DEVICE PROFILE

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**Literature:** Innovations in structural design and device profile can reduce material costs and improve the overall performance and lifespan of the devices.

**Expert Views:** The priority for tidal turbines is to develop robust, reliable tidal turbines that integrate power and structure, considering site-specific conditions and installation/maintenance efficiency, with a focus on survivability over optimization. Optimizing wave energy devices requires balancing ideal designs with manufacturability, using standard materials to reduce costs, and focusing on load-driven structural design tied to power and control strategy.

## ANCHORING AND MOORING

**Literature:** Improving anchoring and mooring systems can lead to cost reductions by ensuring the stability and durability of the devices in harsh marine conditions.

**Expert Views:** Developers are focusing on the reliability and performance of marine energy devices, using known anchoring and mooring solutions to de-risk prototypes, making advanced solutions like piled foundations less of a priority for cost reduction at this stage. Deeper waters increase anchoring and mooring costs, which are often site-specific and vendor-specific, adding complexity; shared mooring could reduce costs but require materials that withstand harsh conditions, and current standards may not be sufficient.

## OPERATIONS AND MAINTENANCE

**Literature:** Streamlining operations and maintenance processes can significantly reduce ongoing costs and improve the reliability of the energy systems.

**Expert Views:** Tidal turbines have shown good resilience by operating for five years without interruption, but maintaining them in harsh environments remains challenging, with some designs enabling efficient maintenance using smaller vessels. Minimizing maintenance in wave energy devices is crucial due to the high costs and challenges of ocean maintenance, and scheduling activities during calm weather periods can reduce risks and costs, especially for larger arrays.

## ARRAYS

**Literature:** Deploying devices in arrays rather than individually can lead to economies of scale and more efficient use of space and resources.

**Expert Views:** Developers are currently focusing on other areas of cost reduction, making arrays less of a priority for optimization as a driver of cost reduction at this stage. Optimizing array design to manage blockage effects is essential for tidal energy, but the lack of in-field data presents a significant challenge, while wave energy array optimization remains a longer-term research area.

## Recommendations

### FUTURE RESEARCH DIRECTION

Due to the scarcity of data, the evolving nature of marine technology, and the complexities of the technologies and their operational environments, a more strategic framework is needed to address challenges in marine energy research. This approach should aim to guide the industry towards specific goals while improving transparency and data availability. To drive commercialization in marine energy

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research, it is essential to have targeted funding focused on innovations with specific objectives, rather than broad, unfocused efforts. Collaboration and sharing of knowledge and resources are crucial for significant progress. Excess optimism in data from developers needs to be addressed to reduce error margins. Research should focus on “known unknowns” and uncertainties, providing accurate data for planning and decision-making. Prioritizing research efforts based on potential return on investment is vital, focusing on areas with the most significant impact on cost reduction and technology development.

Some specific approaches, detailed further below, may include the following:

- **Consortium Model:** A voluntary government-industry partnership enabling pre-competitive information sharing to advance technologies.
- **Technology Validation:** Analysis of real-world data to validate technology performance under realistic conditions, while providing individualized and aggregated analysis results to partners.
- **Inverse LCOE:** Analysis that begins with an LCOE target and works backward to determine the maximum allowable cost for each component of a technology.
- **Funding Innovations with Specific Objectives:** Taking a wholistic view of key drivers, ensuring robust design, and building out technology in incremental steps.

#### CONSORTIUM MODEL

The U.S. DRIVE (*United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability*) Partnership is a consortium model that can serve as a framework for similar models in the marine energy industry.

U.S. DRIVE is a non-legal, non-binding, voluntary government-industry partnership between the U.S. Department of Energy and various automotive, energy, and utility companies (U.S. DRIVE, n.d.). Its goal is to advance R&D in automotive and energy infrastructure technologies to create an affordable, decarbonized transportation system in the U.S.

The partnership enables experts to exchange *pre-competitive* technical information, discuss R&D needs, set joint goals, and evaluate progress. It does not conduct or fund R&D; each partner manages its own projects. By fostering regular interaction among technical experts, the partnership:

- Accelerates technical progress by identifying solutions and evaluating progress toward shared goals.
- Focuses on technology that benefits the nation and avoids duplication, ensuring publicly funded research delivers high value results and overcomes barriers to commercialization.

U.S. DRIVE operates through several groups:

- **Executive Steering Group (ESG):** Oversees high-level technical and management priorities and decisions. Each partner organization has a representative in the ESG – for industry partners, a vice presidential-level executive, and for DOE, the Assistant Secretary for Energy Efficiency and Renewable Energy.
- **Joint Operations Group:** Supports the ESG, manages partnership functions, and coordinates across partner organizations. It manages technical teams and working groups, solves problems,

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reviews and endorses work products, and provides guidance on deliverables. Participants are director-level representatives of partner companies; DOE participation includes Vehicle Technologies and Fuel Cell Technologies Office Directors as well as DOE's U.S. DRIVE Partnership director.

- **Technical Teams:** These teams are the core of the partnership, bringing together partners' top scientists and engineers. They focus on ten key technical areas, identify technology gaps, develop R&D targets, and evaluate progress. All teams meet on a regular basis, typically monthly, and hold joint meetings as needed on cross-cutting topics. Each team develops and maintains a roadmap specific to its focus area and all roadmaps are publicly available.
- **Associate Members:** Represents non-partner organizations which provide additional technical expertise.
- **Working Groups:** Brings together subject-matter experts from U.S. DRIVE partner organizations to focus on a particular issue or task, as directed by the ESG.

U.S. DRIVE partners operate as equals and make a strong commitment to providing top technical expertise and engaging at the management/senior management levels. Both partners and associate members must comply with U.S. anti-trust and competition laws and conduct activities in a way that avoids any appearance of anti-competitive behavior. Each U.S. DRIVE partner makes its own decisions regarding its own funding of projects and programs, according to its own internal policies, requirements, and/or guidelines. No proprietary or government- or company-confidential information is introduced in the partnership process. Decision-making and product approval are based on consensus, with the ESG approving the partnership plan, goals, and targets.

Each year, the Partnership selects technical highlights from many hundreds of DOE-funded projects. The resulting compendium includes one-page summaries that represent what DOE and the automotive, energy, and electric utility industry partners collectively consider to be significant progress in the development of advanced automotive and infrastructure technologies.

### TECHNOLOGY VALIDATION

The National Renewable Energy Laboratory (NREL) implements a technology validation system to analyze data on hydrogen and fuel cell technologies, allowing for a better understanding of technology progress in *real-world* conditions while maintaining the anonymity of data providers (National Renewable Energy Laboratory, 2025). This structure fosters industry confidence in data sharing and could serve as a potential model for the marine energy industry as well. For example, data focus for marine technologies could be on performance curves, failure mode data, and operations and maintenance strategies.

NREL partners with industry to collect and analyze real-world data on hydrogen fuel cell technologies, including fuel cell electric vehicles, fueling infrastructure, system components, and applications like material handling and backup power. These data are used to evaluate performance against DOE targets, identify areas for improvement, and track progress. NREL's Technology Validation team validates that component and system technical targets are met under realistic conditions. Partners share raw data with NREL via the National Fuel Cell Technology Evaluation Center, which securely manages, stores, and processes proprietary industry data. Access is limited to NREL's Technology Validation team, who independently analyze the data and report findings. While raw data are secured to protect proprietary information, individualized analysis results are provided to the partners. These results are also

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aggregated into publicly available composite data products that show the technology's status and progress without identifying individual companies.

### INVERSE LCOE

The conventional LCOE formula simplifies the complexities of electric generation systems. It estimates the present value of building and operating costs for a new plant, with component values based on either technical studies or historical performance. Due to the nascent stage of marine energy technologies and the limited real-world data available, component values may not be as accurate and realistic. Inverse LCOE analysis can be used as an alternative method, where the analysis begins with an LCOE *target* and works backward to determine the *maximum allowable cost for each component*. This approach helps identify cost constraints and make informed decisions on cost allocation. It offers a structured approach to evaluate the economic viability of different cost elements by setting targets for various components based on the desired LCOE.

### FUNDING INNOVATIONS WITH SPECIFIC OBJECTIVES

#### Wholistic View of Key Drivers

The relationships between key drivers in marine energy research are interconnected; changing one driver affects others. The impacts of cost reduction drivers are also technology-specific, meaning that what works for one device type may not work for another. Each marine energy archetype has unique challenges and solutions, making it difficult to establish general cost reduction pathways. Especially for wave energy, selecting the appropriate archetype is the first step.

#### Robust Design

The focus needs to be on increasing **availability**, **survivability**, and **reliability** to improve power performance. No prototype has survived in the water for more than a few months, which is a significant challenge. And achieving higher efficiency might not always be beneficial if the components do not match well. Cheaper, less efficient components can be better if they are properly matched.

#### Incremental Steps

Marine energy faces unique challenges that other renewable technologies, like fuel cells, solar, and wind, did not encounter during their development. Testing the first generation of solar photovoltaics or land-based wind turbines was relatively straightforward because these systems could be easily deployed and tested on land. This allowed for multiple rounds of testing and refinement. In contrast, even small-scale demonstrations of marine energy require setup in harsh marine environments, making site visits and controls more complicated, less feasible, and more costly. Given the urgency to decarbonize our electricity infrastructure, the energy sector has focused its R&D efforts on large, grid-scale renewable energy options. However, it is crucial to prioritize building and testing over theoretical work. Smaller-scale tests are invaluable, as they allow for numerous minor mistakes, which are essential for learning and improvement. Incremental steps, such as scaling up from 10 kW to megawatt-scale, are more effective than leaping from zero to multi-megawatt units. A dynamic environment with a few large projects and many small ones can foster mutual support and enhancement. A moonshot approach may not be as feasible for marine energy. Instead, incremental steps, such as smaller demonstrations including blue economy applications, could help pave the way to larger, grid-scale solutions.

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## 8 APPENDICES

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### Appendix A: Marine Energy Technologies

#### WAVE ENERGY

As the wind passes over oceans, the friction between the wind and the ocean surface transfers energy from the air to the water. The longer the fetch (length of ocean that the wind travels) and the higher the wind's speed, the larger and more energy-packed the waves become. These waves can travel long distances with little energy loss, and most of the energy in waves is concentrated at the surface of the water. The power of waves is determined by their height, wavelength, speed, and the density of the water.

Wave energy converters can be deployed offshore, nearshore, and at shore-based locations. Deeper waters offer greater resources, as the energy in waves decreases near the shore due to friction with the seabed. Wave energy devices need to be designed and built to cope with both regular waves (single frequency) and irregular waves (multiple frequency) coming from multiple directions at different times or at the same time.

Wave energy technologies harness either the kinetic energy, potential energy, or both, from waves. Conversion technologies for capturing wave energy are differentiated by their location, mooring and foundation structures, power take-off systems, conversion methods, and the water's motion and depth. The combination of these characteristics has resulted in numerous technology types. The sector has not yet converged on a single design; new concepts and technologies replace or outnumber those that are being abandoned.

#### Attenuators

Attenuators are floating devices composed of multiple segments and placed in parallel with the waves. They capture energy from the relative motion of these segments as the wave passes them.

#### Point Absorbers

Point absorbers are floating structures which absorb energy from all directions through their movements at/near the water surface. They convert the motion of the buoyant top relative to the base into electricity.

#### Oscillating Water Columns

Oscillating water columns are partially submerged structures that are open to the seawater below the surface, enclosing a column of air on top of a column of water. As waves rise and fall, air is pushed back and forth through an air turbine. The turbine is connected to a rotary generator to create electricity.

#### Overtopping Devices

Overtopping devices capture water as waves break into a reservoir, with the waves filling the reservoir to a level higher than the surrounding ocean. The pressure difference between these two levels forces the water through a turbine and a generator. The operating principle of these devices is similar to conventional hydropower.

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## Oscillating Wave Surge Converters

Oscillating wave surge converters extract energy from wave surges. An arm with a float/flap/membrane swings like a pendulum on a pivot joint, and this motion is converted into electricity.

## TIDAL ENERGY

Tides are the rise and fall of ocean water due to the gravitational effect of the moon and sun on the earth. Tides never stop. Since the relative positions of the sun and moon can be predicted with complete accuracy, tides are very predictable. Tidal current resources are strongest in places with a good tidal range and where currents are sped up by the shape of the coastline and seabed, such as in narrow straits, inlets, around headlands, and between islands.

Tidal power may either be produced by converting the potential energy of the rise and fall of tides (tidal range energy) or the kinetic energy in the incoming (flow) and outgoing (ebb) water (tidal current energy).

*Tidal range* technology is more advanced than other ocean energy technologies and has been used since the 1960s. In this approach, energy is captured when large volumes of water are trapped at high tide behind a barrier and released through turbines at low tide, similar to a dam. However, challenges like limited site availability, high costs, and environmental impacts limit use of this technology.

### Tidal Barrages

Tidal barrages capture water in a holding area, making use of the difference in water height from one side of the barrage to the other. Water is then released through a large turbine or turbines as it flows out with the ebb of the tide. They are typically built across the entrance to a bay or estuary and generate electricity using the difference in water height inside and outside of the structure. A minimum height difference of five meters (16.4 feet) is needed for tidal barrages, making only 40 locations worldwide feasible (Tethys Engineering, n.d.).

*Tidal current* technologies are approaching maturity and are expected to become the prominent tidal power approach. Tidal current turbines extract energy directly from the water currents passing through them. The kinetic energy of tidal currents is converted to mechanical energy as the turbine's blades spin a shaft. The mechanical energy in the shaft is converted to electrical energy through a connection to a generator. Tidal turbines installed to date are generally at high maturity levels, with technology readiness levels ranging from eight to nine. These turbines have capacities ranging from 100 kW up to over 2 MW per device (du Fornel et al., 2024). While they are similar to those used in the wind energy sector, the higher density of seawater compared to air allows tidal turbines to capture equivalent energy with smaller turbines and slower movement.

### Axial Flow Turbines

Axial flow turbines are like traditional wind turbines, capturing the kinetic energy of moving water by spinning blades facing the direction of flow. Turbines can be placed anywhere in the water column, though bottom-mounted is the most common, and they can also have pitching blades to adapt to varying flow conditions.

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## Cross-Flow Turbines

Cross-flow turbines have spinning blades oriented perpendicularly to the direction of the flow and can be mounted either vertically or horizontally. Turbines can be placed anywhere in the water column, though bottom-mounted is the most common, and are well-suited for placement in confined channels.

## Reciprocating Devices

Reciprocating devices have a hydrofoil that is pushed back and forth across the flow direction by lift or drag. The devices may be oriented horizontally or vertically but must face the direction of flow for maximum energy extraction. The linear motion of the foils is converted to rotary motion for electricity generation, or linear generators are used.

## Tidal Kites

Tidal kites feature a hydrodynamic wing with an attached turbine that is tethered to a fixed point by a cable. The flow of water lifts the wing, and as it loops through the water, it pulls the turbine through the water at speeds several times higher than the actual stream speed, allowing more energy extraction even in slower currents. The turbine is connected to a generator that produces electricity.

## Archimedes' Screw

Archimedes' screw is a helical surface surrounding a cylindrical shaft, generating energy as water flow moves up the spiral and rotates the device, which is coupled to a generator through a gearbox.

## OTHER MARINE ENERGY

OTEC and salinity gradient technologies are still in early development stages with limited deployed demonstration projects and not much research has been conducted with regards to ocean current technology.

### Ocean Thermal Energy Conversion

OTEC uses thermal heat engines to generate energy from the temperature difference between the warm surface waters of the ocean and the colder depths. The temperature difference needs to be about 20 °C (68 °F), which means that the surface temperature should be around 25 °C (77 °F), as deep-sea water at 1,000 m (3,281 ft) depth is a constant 4 °C (39.2 °F). This restricts OTEC technology to mostly the tropical regions.

Various OTEC archetypes are being investigated. OTEC devices can be configured to be open or closed cycle or hybrid systems. The difference between the systems relates to the working fluid used and its recycling. Open-cycle systems use warm seawater, whereas closed-cycle systems use another fluid (e.g., ammonia) and recycle it through the system. The warm working fluid is vaporized and drives a turbine to generate electricity. OTEC technology can also be coupled with technologies such as seawater air conditioning to provide cooling and seawater reverse osmosis to produce fresh water, and the wastewater of the electricity generation can be repurposed for aquaculture use.

### Salinity Gradient Energy

Salinity gradient technologies generate energy from the difference in salt concentration between saltwater and freshwater.

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- *Pressure retarded osmosis* converts the osmotic pressure of saltwater to hydraulic pressure, which drives a turbine and generates electricity.
  - *Reverse electrodialysis* generates electricity from the controlled mixing of two water bodies with different salinities. Membranes create compartments with high and low salt levels. When saltwater and freshwater pass through these membranes, the movement of positively and negatively charged ions creates charged poles like a battery.

### **Ocean Current Energy**

Ocean currents are driven by factors such as wind, depth, temperature, salinity, and the rotation of the Earth. They are constant in both speed and flow, and their energy can be captured using turbines. While these turbines are similar to those used to capture energy from tidal currents, they can operate at lower flow speeds and may not need to account for reversing flow. Ocean currents are generally located further offshore than tidal currents, requiring deployment of turbines in deeper water. The strongest ocean currents are also found higher in the water column, requiring floating designs.

## Appendix B: Prioritization of Key Drivers

Converter Type	Archetype	Key Driver	LCOE reduction % (low)	LCOE reduction % (high)	WPTO Activity Area	Reference
wave energy converter	attenuator	advanced controls	----	----	Foundational R&D	<a href="#">SAND2013-7207</a>
wave energy converter	attenuator	anchoring & mooring	----	----	Foundational R&D	<a href="#">SAND2013-7207</a>
wave energy converter	attenuator	array optimization	----	----	System Design & Validation	<a href="#">SAND2013-7207</a>
wave energy converter	attenuator	installation & deployment	----	----	System Design & Validation	<a href="#">SAND2013-7207</a>
wave energy converter	attenuator	O&M	----	----	System Design & Validation	<a href="#">SAND2013-7207</a>
wave energy converter	attenuator	power	----	----	Foundational R&D	<a href="#">SAND2013-7207</a>
wave energy converter	attenuator	structural design & device profile	----	----	Foundational R&D	<a href="#">SAND2013-7207</a>
wave energy converter	attenuator	structural design & device profile	----	----	Foundational R&D	<a href="#">SAND2013-7207</a>
wave energy converter	attenuator	system reliability	----	----	System Design & Validation	<a href="#">SAND2013-7207</a>
current energy converter	tidal current turbine	advanced controls	----	----	Foundational R&D	<a href="#">SAND2013-7203</a>
current energy converter	tidal current turbine	array optimization	----	----	System Design & Validation	<a href="#">SAND2013-7203</a>
current energy converter	tidal current turbine	common components (across offshore renewables)	----	----	Foundational R&D	<a href="#">SAND2013-7203</a>
current energy converter	tidal current turbine	design for manufacturing & component standardization	----	----	Foundational R&D	<a href="#">SAND2013-7203</a>
current energy converter	tidal current turbine	grid connection	----	----	System Design & Validation	<a href="#">SAND2013-7203</a>
current energy converter	tidal current turbine	installation & deployment	----	----	System Design & Validation	<a href="#">SAND2013-7203</a>
current energy converter	tidal current turbine	materials and coatings	----	----	Foundational R&D	<a href="#">SAND2013-7203</a>

Converter Type	Archetype	Key Driver	LCOE reduction % (low)	LCOE reduction % (high)	WPTO Activity Area	Reference
current energy converter	tidal current turbine	power	----	----	Foundational R&D	<a href="#">SAND2013-7203</a>
current energy converter	tidal current turbine	structural design & device profile	----	----	Foundational R&D	<a href="#">SAND2013-7203</a>
current energy converter	tidal current turbine	system reliability	----	----	System Design & Validation	<a href="#">SAND2013-7203</a>
wave energy converter	oscillating water column	advanced controls	----	----	Foundational R&D	<a href="#">SAND2013-7205</a>
wave energy converter	oscillating water column	anchoring & mooring	----	----	Foundational R&D	<a href="#">SAND2013-7205</a>
wave energy converter	oscillating water column	array optimization	----	----	System Design & Validation	<a href="#">SAND2013-7205</a>
wave energy converter	oscillating water column	O&M	----	----	System Design & Validation	<a href="#">SAND2013-7205</a>
wave energy converter	oscillating water column	power	----	----	Foundational R&D	<a href="#">SAND2013-7205</a>
wave energy converter	oscillating water column	structural design & device profile	----	----	Foundational R&D	<a href="#">SAND2013-7205</a>
wave energy converter	oscillating water column	structural design & device profile	----	----	Foundational R&D	<a href="#">SAND2013-7205</a>
wave energy converter	oscillating water column	system reliability	----	----	System Design & Validation	<a href="#">SAND2013-7205</a>
wave energy converter	point absorber	advanced controls	----	----	Foundational R&D	<a href="#">SAND2013-7204</a>
wave energy converter	point absorber	anchoring & mooring	----	----	Foundational R&D	<a href="#">SAND2013-7204</a>
wave energy converter	point absorber	array optimization	----	----	System Design & Validation	<a href="#">SAND2013-7204</a>
wave energy converter	point absorber	power	----	----	Foundational R&D	<a href="#">SAND2013-7204</a>
wave energy converter	point absorber	structural design & device profile	----	----	Foundational R&D	<a href="#">SAND2013-7204</a>
wave energy converter	point absorber	structural design & device profile	----	----	Foundational R&D	<a href="#">SAND2013-7204</a>
wave energy converter	point absorber	system reliability	----	----	System Design & Validation	<a href="#">SAND2013-7204</a>

Converter Type	Archetype	Key Driver	LCOE reduction % (low)	LCOE reduction % (high)	WPTO Activity Area	Reference
current energy converter	tidal current turbine	advanced controls	5.0	10.0	Foundational R&D	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	anchoring & mooring	5.0	10.0	Foundational R&D	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	array optimization	10.0	20.0	System Design & Validation	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	blades	2.0	5.0	Foundational R&D	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	cables	2.0	5.0	System Design & Validation	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	insurance	----	----	N/A	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	permitting	----	----	System Design & Validation	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	power	5.0	10.0	Foundational R&D	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	rotor diameter	20.0		Foundational R&D	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	subsea hub usage	10.0	20.0	System Design & Validation	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	warranties	----	----	N/A	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	wet mate connectors	2.0	5.0	System Design & Validation	<a href="#">ORE Catapult Tidal Roadmap</a>
current energy converter	tidal current turbine	anchoring & mooring	3.4		Foundational R&D	<a href="#">TIGER (Tidal Stream Industry Energiser)</a>
current energy converter	tidal current turbine	blades	3.0		Foundational R&D	<a href="#">TIGER (Tidal Stream Industry Energiser)</a>
current energy converter	tidal current turbine	power	4.7		Foundational R&D	<a href="#">TIGER (Tidal Stream Industry Energiser)</a>
current energy converter	tidal current turbine	rotor diameter	24.1		Foundational R&D	<a href="#">TIGER (Tidal Stream Industry Energiser)</a>
current energy converter	tidal current turbine	rotor diameter + power output	37.7		Foundational R&D	<a href="#">TIGER (Tidal Stream Industry Energiser)</a>
current energy converter	tidal current turbine	scale-up (100 MW)	28.4		System Design & Validation	<a href="#">TIGER (Tidal Stream Industry Energiser)</a>

Converter Type	Archetype	Key Driver	LCOE reduction % (low)	LCOE reduction % (high)	WPTO Activity Area	Reference
current energy converter	tidal current turbine	subsea hub usage	8.0		System Design & Validation	<a href="#">TIGER (Tidal Stream Industry Energiser)</a>
current energy converter	tidal current turbine	weighted average cost of capital	9.6		N/A	<a href="#">TIGER (Tidal Stream Industry Energiser)</a>
current energy converter	tidal current turbine	wet mate connectors	6.4	----	System Design & Validation	<a href="#">TIGER (Tidal Stream Industry Energiser)</a>
wave energy converter	not identified	anchoring & mooring	----	----	Foundational R&D	<a href="#">NREL/TP-5700-82375</a>
wave energy converter	not identified	O&M	----	----	System Design & Validation	<a href="#">NREL/TP-5700-82375</a>
wave energy converter	not identified	power	----	----	Foundational R&D	<a href="#">NREL/TP-5700-82375</a>
wave energy converter	not identified	structural design & device profile	----	----	Foundational R&D	<a href="#">NREL/TP-5700-82375</a>
current energy converter	not identified	O&M	----	----	System Design & Validation	<a href="#">NREL/CP-5000-64013</a>
wave energy converter	not identified	O&M	----	----	System Design & Validation	<a href="#">NREL/CP-5000-64013</a>
current energy converter	not identified	power	----	----	Foundational R&D	<a href="#">NREL/CP-5000-64013</a>
wave energy converter	not identified	power	----	----	Foundational R&D	<a href="#">NREL/CP-5000-64013</a>
wave energy converter	not identified	power	----	----	Foundational R&D	<a href="#">NREL/CP-5000-64013</a>
wave energy converter	not identified	structural design & device profile	----	----	Foundational R&D	<a href="#">NREL/CP-5000-64013</a>
current energy converter	tidal current turbine	O&M	----	----	System Design & Validation	<a href="#">IEA-OES International LCOE</a>
wave energy converter	not identified	O&M	----	----	System Design & Validation	<a href="#">IEA-OES International LCOE</a>
current energy converter	tidal current turbine	structural design & device profile	----	----	Foundational R&D	<a href="#">IEA-OES International LCOE</a>
wave energy converter	not identified	structural design & device profile	----	----	Foundational R&D	<a href="#">IEA-OES International LCOE</a>
wave energy converter	not identified	anchoring & mooring	----	----	Foundational R&D	<a href="#">SAND2016-8298C</a>

Converter Type	Archetype	Key Driver	LCOE reduction % (low)	LCOE reduction % (high)	WPTO Activity Area	Reference
current energy converter	tidal current turbine	PTO	----	----	Foundational R&D	<a href="#">SAND2016-8298C</a>
wave energy converter	not identified	PTO	----	----	Foundational R&D	<a href="#">SAND2016-8298C</a>
current energy converter	tidal current turbine	structural design & device profile	----	----	Foundational R&D	<a href="#">SAND2016-8298C</a>
wave energy converter	not identified	structural design & device profile	----	----	Foundational R&D	<a href="#">SAND2016-8298C</a>
current energy converter	tidal current turbine	array optimization	28.0	40.0	System Design & Validation	<a href="#">Frazer-Nash Tidal LCOE</a>
current energy converter	tidal current turbine	rotor diameter + power output	17.0	23.0	Foundational R&D	<a href="#">Frazer-Nash Tidal LCOE</a>
wave energy converter	not identified	anchoring & mooring	----	----	Foundational R&D	<a href="#">WES Landscaping Study</a>
wave energy converter	not identified	PTO	----	----	Foundational R&D	<a href="#">WES Landscaping Study</a>
wave energy converter	not identified	structural design & device profile	----	----	Foundational R&D	<a href="#">WES Landscaping Study</a>
current energy converter	tidal current turbine	anchoring & mooring	----	----	Foundational R&D	<a href="#">TIGER Cost Reduction Tidal UK and France</a>
current energy converter	tidal current turbine	blades	----	----	Foundational R&D	<a href="#">TIGER Cost Reduction Tidal UK and France</a>
current energy converter	tidal current turbine	PTO	----	----	Foundational R&D	<a href="#">TIGER Cost Reduction Tidal UK and France</a>
current energy converter	tidal current turbine	rotor diameter + power output	----	----	Foundational R&D	<a href="#">TIGER Cost Reduction Tidal UK and France</a>
current energy converter	tidal current turbine	anchoring & mooring	----	----	Foundational R&D	<a href="#">ETIP Ocean</a>
wave energy converter	not identified	anchoring & mooring	----	----	Foundational R&D	<a href="#">ETIP Ocean</a>
current energy converter	tidal current turbine	PTO	----	----	Foundational R&D	<a href="#">ETIP Ocean</a>
wave energy converter	not identified	PTO	----	----	Foundational R&D	<a href="#">ETIP Ocean</a>
wave energy converter	not identified	structural design & device profile	----	----	Foundational R&D	<a href="#">ETIP Ocean</a>

Converter Type	Archetype	Key Driver	LCOE reduction % (low)	LCOE reduction % (high)	WPTO Activity Area	Reference
wave energy converter	not identified	PTO	----	----	Foundational R&D	<a href="#">ENTEC UK</a>
wave energy converter	not identified	structural design & device profile	----	----	Foundational R&D	<a href="#">ENTEC UK</a>

## Appendix C: Supplementary Graphics

ORE Catapult<sup>2</sup> has indicated that just eight drivers alone can play a role in reducing tidal energy’s levelized cost of energy by 67.5%, with six of these drivers being technological. Increased rotor diameter, and especially when considered together with increased rated power, has the biggest effect on bringing costs down.

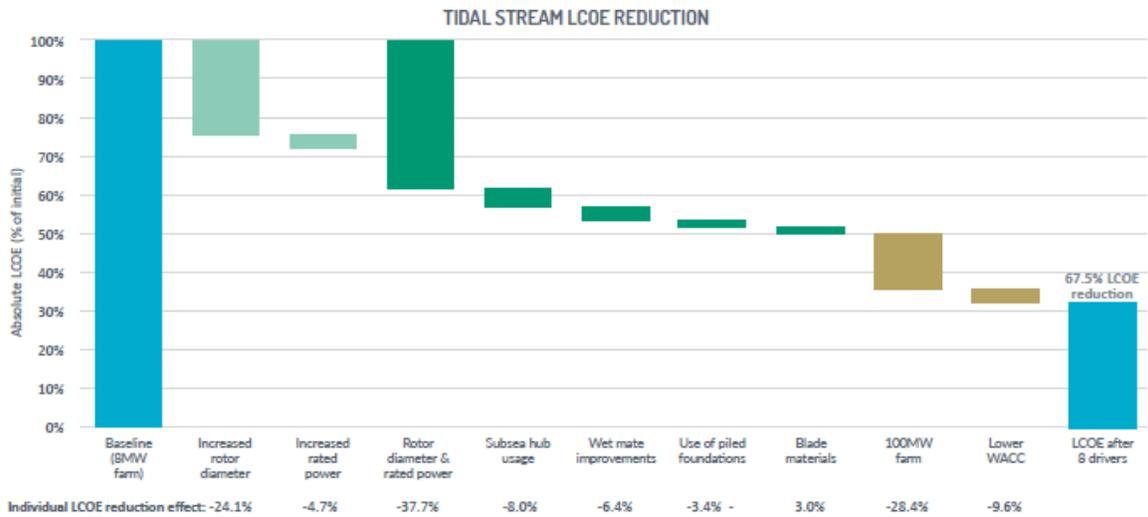


Figure 1: LCoE reduction of 67.5% that can be achieved by eight cost reduction drivers. Rotor diameter & rated power represents the additive nature of the two previous innovations (highlighted in light green). 100MW farm and Lower WACC are economic drivers (highlighted in gold) [3]

<sup>2</sup> ORE Catapult. (2024). *Tidal stream technology roadmap* (Revision 1). Offshore Renewable Energy Catapult. <https://cms.ore.catapult.org.uk/wp-content/uploads/2024/03/ORE-Catapult-Tidal-stream-roadmap-report-2024.pdf>.

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## Appendix D: Resources Used in Determining Key Drivers

The resources listed below are the 15 that had information on key drivers, with 9 out of the 15 offering more granular information and 3 out of the 15 including quantitative information.

YEAR	AUTHOR(S)	ORGANIZATION	TITLE	GRANULAR INFO?	QUANTITATIVE INFO?
2022	Baca, E., Philip, R. T., Greene, D., and Battey, H.	National Renewable Energy Laboratory	<a href="#">Expert Elicitation for Wave Energy LCOE Futures (NREL/TP-5700-82375)</a>	✓	----
2013a	Bull, D. and Ochs, M. E.	Sandia National Laboratories	<a href="#">Technological cost-reduction pathways for attenuator wave energy converters in the marine hydrokinetic environment (SAND2013-7207)</a>	✓	----
2013b	Bull, D. and Ochs, M. E.	Sandia National Laboratories	<a href="#">Technological cost-reduction pathways for oscillating water column wave energy converters in the marine hydrokinetic environment (SAND2013-7205)</a>	✓	----
2013	Bull, D., Ochs, M. E., Laird, D. L., Boren, B., and Jepsen, R. A.	Sandia National Laboratories	<a href="#">Technological cost-reduction pathways for point absorber wave energy converters in the marine hydrokinetic environment (SAND2013-7204)</a>	✓	----
2006	N/A	Entec UK Ltd. (for the Carbon Trust)	<a href="#">Cost estimation methodology: The Marine energy challenge approach to estimating the cost of energy produced by marine energy systems</a>	----	----
2023	N/A	Frazer-Nash Consultancy	<a href="#">Review of technical assumptions and generation costs: Levelised cost of electricity from tidal stream energy (Issue 1.1, Project No. 017344)</a>	✓	✓
2022a	Frost, C.	TIGER (Tidal Stream Industry Engisier)	<a href="#">Cost reduction pathway of tidal stream energy in the UK and France (Volume 1.0)</a>	----	----
2022b	Frost, C.	TIGER (Tidal Stream Industry Engisier)	<a href="#">T3.2.2 Tidal stream site cost reduction report (Version 2.0)</a>	✓	✓
2015	N/A	International Energy Agency	<a href="#">International levelised cost of energy for ocean energy technologies</a> IEA Technology Collaboration Programme for Ocean Energy Systems (OES)	----	----
2015	Jenne, D. S., Yu, Y.-H., and Neary, V.	National Renewable Energy Laboratory	<a href="#">Levelized cost of energy analysis of marine and hydrokinetic reference models (NREL/CP-5000-64013)</a>	✓	----

YEAR	AUTHOR(S)	ORGANIZATION	TITLE	GRANULAR INFO?	QUANTITATIVE INFO?
2013	Laird, D. L., Johnson, E. L., Ochs, M. E., and Boren, B	Sandia National Laboratories	<a href="#">Technological cost-reduction pathways for axial-flow turbines in the marine hydrokinetic environment (SAND2013-7203)</a>	✓	----
2016	Neary, V. S., Kobos, P., Jenne, D. S., and Yu, Y.-H.	Sandia National Laboratories	<a href="#">Levelized cost of energy for marine energy conversion (MEC) technologies (SAND2016-8298C)</a>	----	----
2017	N/A	Wave Energy Scotland	<a href="#">Application of technology, knowledge and practice from other sectors: Landscaping study</a>	----	----
2024	N/A	Offshore Renewable Energy Catapult	<a href="#">Tidal stream technology roadmap (Revision 1)</a>	✓	✓
2024	Ruiz-Minguela, P., Berque, J., Villate, J. L., Pirttimaa, L., Gruet, R., Noble, D., and Jeffrey, H.	European Technology & Innovation Platform for Ocean Energy	<a href="#">Strategic research and innovation agenda for ocean energy</a>	----	----

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