TIGER TIDAL STREAM INDUSTRY ENERGISER

EUROPEAN UNION
European Regional
Development Fund

T3.2.2 Tidal Stream Site Cost Reduction Report

V2.0

Oct 2022

Interreg
EUROPEAN UNION
France (Channel Manche) England
European Regional Development Fund

Document History

Revision	Date	Description	Originated by	Reviewed by	Approved by
2.0	Nov 2022	Final version	CF	MY	SC
1.0	Apr 2022	Draft for TIGER partner review	CF	GS	SC

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Acronyms

Acronym	Description
CAPEX	Capital expenditure
CfD	Contracts for Difference
DECEX	Decommissioning expenditure
ERDF	European Regional Development Fund
FCE	France (Channel Manche) England
LCOE	Levelised cost of energy
O&M	Operations and maintenance
OPEX	Operational expenditure
ORE Catapult	Offshore Renewable Energy Catapult
PPA	Power purchase agreement
PTO	Power take-off
RO	Renewables Obligation
ROCs	Renewables Obligation Certificates
ROV	Remotely operated vehicle
TSE	Tidal stream energy
WACC	Weighted average cost of capital

Executive Summary

Tidal stream energy (TSE) is seeing renewed interest across the world, especially in the UK, France and Canada. In 2021, the UK government committed to supporting the sector via revenue support in CfD Allocation Round 4 (AR4), to the sum of £20M per annum for 15-year CfD contracts, while in France there is talk of a power purchase agreement (PPA).

Such favourable government headwinds are promising for the sector in the short term, particularly when the security of supply has come back onto the agenda. However, to properly capitalise, the industry needs to be able to demonstrate a future pathway towards a low levelized cost of energy (LCOE).

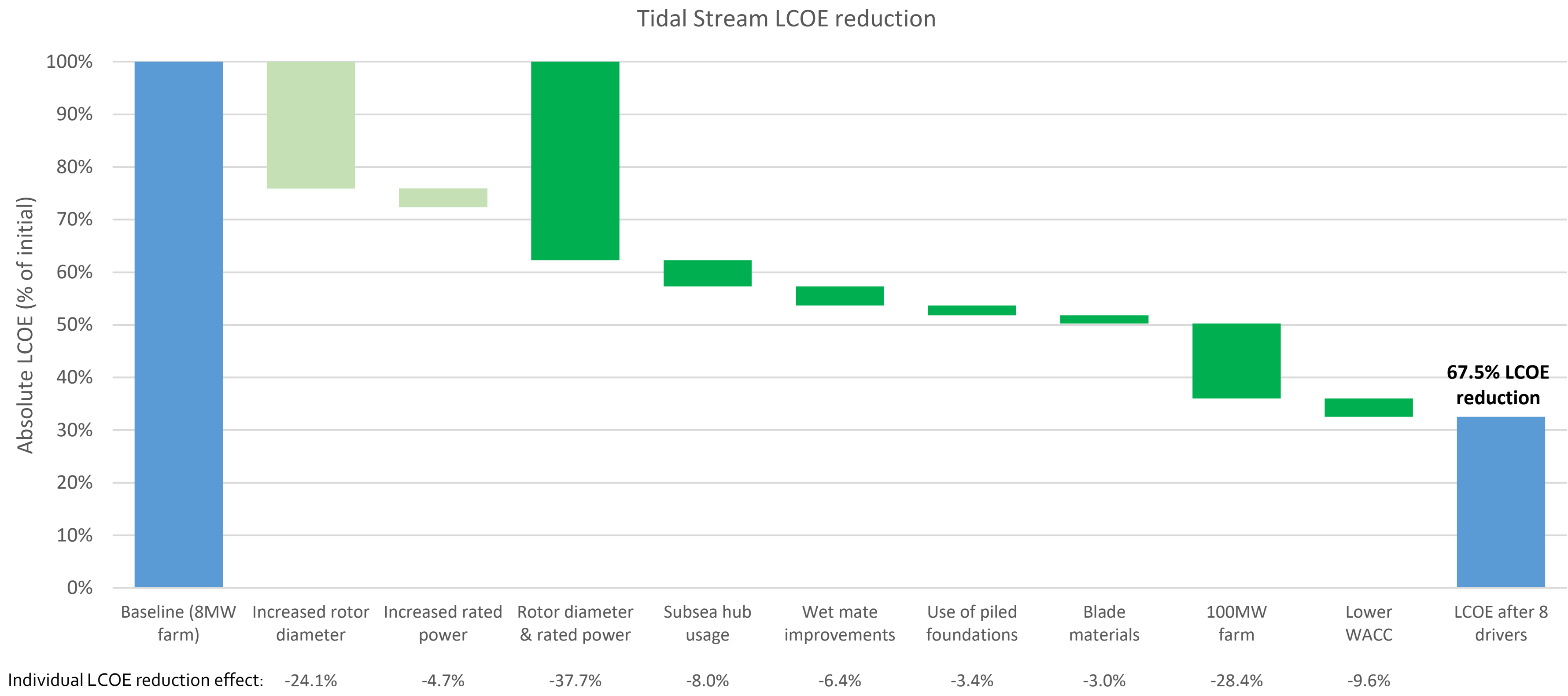
TSE has significant benefits over other renewables, including its high predictability, regular cyclical pattern and the fact that it is completely decoupled from other renewable resources like wind and solar. This means that it can provide electricity when other renewables might not be able to, and equally reduce the curtailment that could occur in the case of extreme weather. This, however, is not enough. The industry needs to prove that it can produce energy at a competitive cost that provides benefits to the grid, and the wider economy, despite perhaps never quite reaching price comparability with offshore wind.[1]

In this report we examine the key cost reduction drivers that will allow the industry to reach this economic competitiveness. This involved the following stages:

- We produced a list of over 50 innovations and cost reduction drivers. We narrowed this down to eight drivers[2], those judged to have the most significant cost reduction benefits in the short to medium term. We reviewed the literature to highlight the current state of the art and summarise the benefits in these areas.
- We created a model to examine the impacts of these drivers on annual energy production (AEP), costs and LCOE for a baseline farm. The baseline we assumed was a farm of four 2MW devices, commissioned in 2021.
- We estimated the impacts using data from TIGER partners, literature review and our knowledge of offshore wind cost reduction mechanisms.
- We compared the drivers, to understand which showed the most promise, and also discussed them in the context of tidal sites in the Channel region (between the UK and France).

[1] As evidenced by the Allocation Round 4 Administrative Strike Prices: £211/MWh for tidal stream compared to £46/MWh for offshore wind (£2012 prices) [104]

[2] Nine including the combined impact of larger rotor diameter and larger rated power which were considered together as an additional driver



LCOE reduction that can be achieved by the cost reduction drivers examined. The increased rotor diameter and rated power represents the additive nature of the two previous innovations (in lighter green).

The combined impact of the drivers, showing the relative improvements in LCOE that could be captured, is shown on the previous page. Our conclusions and recommendations can be summarised as follows:

- We calculated the overall LCOE reduction from the eight innovations to be 67.5%, taking the LCOE down to £99/MWh (£78/MWh in £2012 currency[3]). This included the combined benefits of increasing turbine rotor diameter and rated power, with greater reduction than the sum of the two individual drivers.
- The most significant LCOE reduction drivers were found to be increasing device rotor diameter and rated power (38% reduction), upscaling to a 100MW farm (28% reduction), 20% reduction in WACC (10% reduction) and implementation of subsea hubs (8% reduction).
- The majority of the drivers could be implemented by 2030, possibly with the exception of large economies of volume and WACC reduction which would require further financial de-risking.
- There is the potential to adopt these innovations across sites in the Channel region.
    - Larger sites (capable of supporting multiple 100MW+ farms) like the Raz Blanchard and Isle of Wight (PTEC and Portland Bill) could see substantial benefits from larger rotors and economies of volume from larger farms.
    - Mid scale sites (<100MW) like Morbihan Gulf could harness cost reduction through economies of volume and also technical improvements like improved wet mate connectors and blade materials.
    - Small to mid scale sites (<50MW) like Ramsey Sound, Paimpol-Bréhat and Yarmouth Harbour (near the Isle of Wight) could test the next generation of device innovations in real sea conditions, and small commercial projects could benefit from targeted technical innovations.
- We recommend the following:
    - Further research into larger rotors and blades, as these offer the best early way to drive down LCOE. Accelerated life testing at facilities like ORE Catapult's 50m test rig and University of Edinburgh's FastBlade could be combined with more detailed techno-economic modelling and validation in the field. Manufacturing considerations are also key, especially in the context of potential next generation materials like thermoplastics.
    - Establishment of a cost monitoring framework or similar, so the industry can track progress against these innovation targets and demonstrate a clear and

[3] 2012 is base year for CfD strike prices.

credible cost reduction trajectory to government (including independent third-party review).

- Closer alignment between tidal technology developers and the financial community, to further investigate alternative financing arrangements which will unlock further cost reduction potential.

1. Introduction

Tidal stream energy (TSE) is an exciting, emerging technology. While deployment to date has largely been limited to single turbines and proof of concept demonstration, the industry is on a cusp of a new dawn, with £20M per annum ringfenced by the UK Government for the industry through Allocation Round 4 (AR4). Results are expected in 2022 and could see 30-40MW of new tidal capacity announced. Commissioning of these projects could occur as early as 2025, benefitting from site leases already in place.

TSE has key benefits over other renewable technologies:

- Close synergies with offshore wind technology. The majority of device concepts utilize horizontal axis rotors with similar powertrain components and configuration. This means that offshore wind supply chains can be utilized with access to similar cost reduction pathways.
- Tidal sites tend to be close to shore. For example, utilising the tidal flows channelled around headlands and between islands. This reduces the amount of export cable and transmission cost in the system.
- Tidal flows are driven by the relative movements of the Earth, Moon and Sun. This means that the tidal resource is highly predictable and can be forecast hundreds of years into the future, thus reducing grid balancing requirements and associated costs (for example curtailment costs and costs of bringing more capacity online at short notice).
- The nature of the tidal resource means that it is completely uncoupled from other renewable resources, including wind and solar. This timing difference has potential advantages for the energy system, helping to provide a more consistent supply and reducing curtailment.

Despite these, deployment TSE has lagged behind compared to other renewables like wind and solar. The main reason for this is that the technology is still relatively expensive. This is best illustrated by the high administrative strike price for AR4, £211/MWh compared to £46/MWh for offshore wind, £47/MWh for commercial solar PV (>5MW) and £62/MWh for remote island wind [1].

The long-term success of the industry depends on its ability to compete with these types of renewables, as there are many possible pathways towards the UK and French 2050 net zero targets. Any price premium afforded to tidal will ultimately come at the expense of the taxpayer, and so evidence of cost reduction and value will ensure that the industry is supported by governments into the future and can provide a meaningful contribution to the electricity system.

There are many cost reduction drivers that could revolutionise the industry, some more straightforward than others. This study describes the leading cost reduction drivers and innovations ("drivers") and quantifies the impact on the levelised cost of energy (LCOE) for those deemed the most significant.

1.1. Aims and objectives

The aim of this study is:

To showcase the leading cost reduction drivers in the tidal stream sector by describing the current state-of-the-art research and quantifying the impact of these drivers on LCOE.

The following objectives were devised to achieve this:

- Identify as many cost reduction drivers in the TSE industry as possible through literature review and engagement with industry experts.
- Devise a short list of innovations to analyse.
- Create a techno-economic model in Microsoft Excel to examine the impact of different cost drivers.
- Devise a base case 2022 tidal farm, assuming an appropriate technology, and devise representative project costs from available data.
- Quantify the impact of each selected driver on LCOE to allow them to be compared
- Evaluate the cost reduction drivers in the context of the six tidal stream sites currently being supported as part of the TIGER project.

1.2. Literature review: innovation priorities

Across the industry there is general consensus on the barriers to cost reduction that should be targeted. While the priorities are different across different device concepts, there are some themes which are prevalent across the industry as a whole. This section introduces previous studies that have attempted to detail and, in some cases, rank the key areas of focus. In particular, this study has been designed to build upon the first study mentioned below, published by ORE Catapult in 2018.

Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit (2018) [2]

In this report, the authors found that TSE could reach an LCOE of £150/MWh with 100MW installed, reducing to £90/MWh after 1GW and £980/MWh after 2GW.

The cost trajectory that was devised is shown in Figure 1. A large amount of initial reduction was envisioned through deploying devices in the water, including sub-1MW devices, to quickly gain knowledge and take advantage of learning-based cost reduction effects. Key areas where technical innovations could be utilised were identified:

- Improved reliability and availability

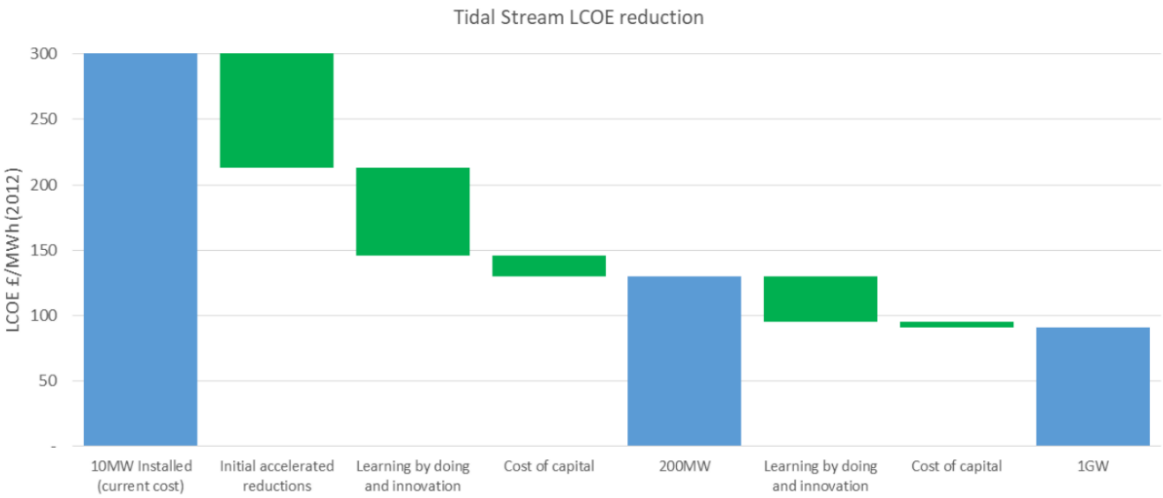


Figure 1 – Tidal stream cost reduction pathway, as devised by ORE Catapult in 2018 [2].

- Improved structures and moorings
- Reduced offshore operational costs
- Improved electrical connectors.

Moreover, the authors identified the cost of capital as an LCOE driver. They predicted that this could fall from 10% in 2018 (whereby projects are financed through equity, with little to no debt) to 7.1% by the time that 2GW is installed (25% debt at a 4.5% interest rate and 75% equity at an 8% return). However, they acknowledged that this assumption is somewhat conservative compared to the offshore wind (where more debt financing has been realised than previously predicted) and concluded that a 1% reduction in discount rate equates to about a 6% reduction in LCOE.

Further into the future the authors assumed long-term learning rates of 13% for capital expenditure (CAPEX) and 11% for operational expenditure (OPEX); these were cross-checked against the literature and historic learning rates seen for other renewable technologies.

Tidal Stream: Opportunities for Collaboration (2019) [3]

ORE Catapult followed up the above study with this publication. It described areas for leading tidal stream developers to collaborate on, prioritising those which could facilitate capacity deployment and improve the export potential for UK companies. The focus was centred on SIMEC Atlantis Energy, Nova Innovation and Orbital Marine Power, although the identified themes were (and still are) relevant to the whole sector.

The report suggested building a collaborative action plan to drive down costs through shared learning. Priority areas were identified as:

- *Turbine blades:* It is noted that tidal turbine blades can cost 3-4 times more per kg compared to wind turbine blades due to the high cost of tooling and low volumes. Differences in turbines scales and specific flow conditions at the site make collaboration in this area challenging.

- *Pitch control:* Wind turbine pitch control systems are unsuitable, making this an area for development. Not all devices have pitch control. For the ones that do, the pitch control system has a huge impact on yield, with the potential to increase lead times and costs.
- *Subsea hubs*: As a way to reduce cabling cost to shore, of more relevance to fixed bottom devices.
- *Wet mate connectors*: Suitable connectors could reduce the cost of turbine deployment/retrieval by 65%. The author notes that wet mate connectors are not typically designed for tidal applications, and more research needs to be done to integrate within subsea hubs.
- Deployment and recovery of devices: Technologies that could allow smaller and locally owned vessels to be used to reduce reliance on large and expensive vessels.

The role of testing, validation and demonstration was also touted as key and could allow projects to secure lower insurance costs and better financing conditions through de-risking.

Lastly, the author identifies large-scale projects, access to commercial debt and a move away from gravity anchors as important cost drivers.

Energy Innovation Needs Assessment: Tidal Stream (2019) [4]

This study was led by Vivid Economics and commissioned by the UK Department for Business, Energy & Industrial Strategy (BEIS). Part of the work listed the key innovations accessible to the industry, as well as the market barriers that would prevent these innovations from being fully utilised. These were identified through industry engagement, with the purpose of the study to identify priority areas for public funding.

The system areas where innovation was judged to have the biggest cost reduction potential were:

- *Structure and prime mover*: Implementation of novel materials and improved blade designs.
- *Power take-off (PTO) and control*: Use of permanent magnet generators, advanced control systems to minimise fatigue and improve yield, improved pitch and yaw technology.
- *Foundations and moorings*: Lower cost foundations and mooring systems for floating devices, with learning from offshore wind.

- *Operations and maintenance (O&M)*: Improvements to reduce time at sea and duration of operations, for example advanced metocean monitoring, condition monitoring systems, improved processes and procedures, and use of remotely operated vehicles (ROVs).
- *Yield*: Improvements in resource modelling to improve system design, allow better siting of turbines and improve knowledge of reliability.

Based on these thematic areas, 24 specific innovation areas were identified and qualitatively assessed: based on their impact on cost reduction and how well they could reduce future barriers to market entry. Timeframes were also provided. Generally, innovations in the "structure and prime mover" category featured highly in the rankings, including advanced blade manufacturing, new and improved blade technology and advanced PTO technologies. This also varied between fixed and floating technologies: with more emphasis on O&M for fixed and moorings and control systems for floating.

ETIP Ocean: Strategic Research and Innovation Agenda for Ocean Energy (2020) [5]

ETIP Ocean is an advisory body to the European Commission, working within the EU Research and Innovation policy: the Strategic Energy Technology Plan (SET-Plan) [6].

This study was conducted by a consortium of Ocean Energy Europe, Technalia, WAVEC and the University of Edinburgh. They highlight the crucial role that research and development has to play in unlocking cost reduction by presenting the main "challenge areas" and, within each, the "priority topics" that will provide the greatest benefit to the sector over the next 4-5 years. Figure 2 shows how the organisation foresees the

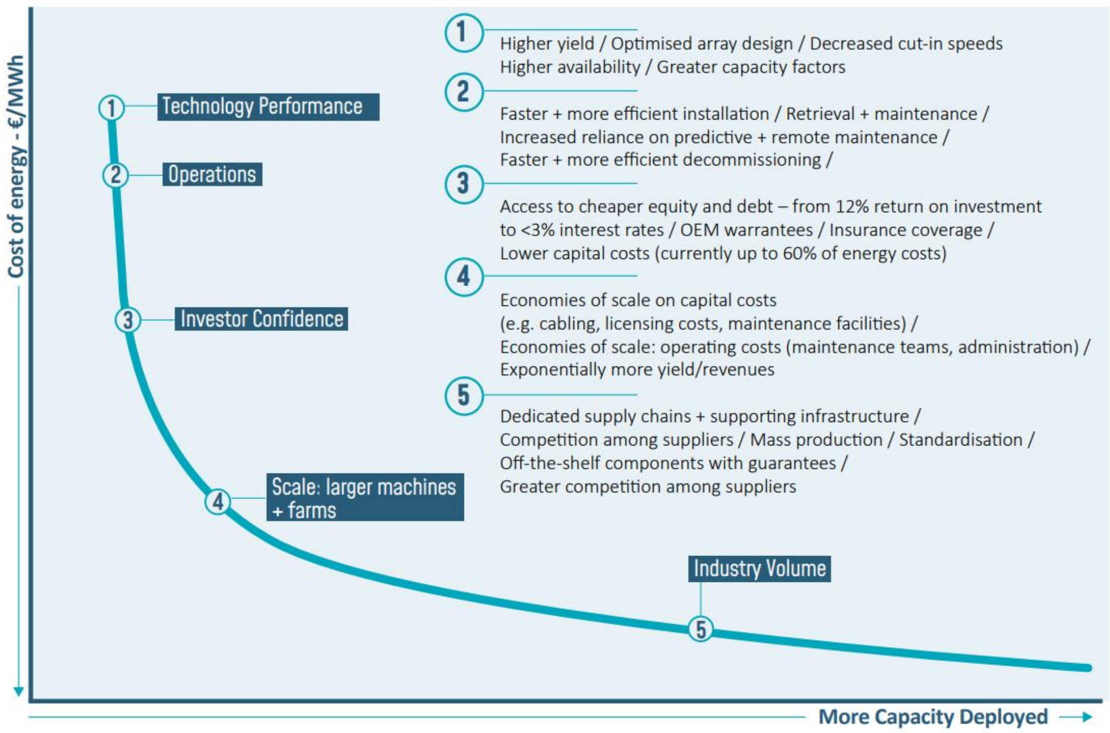


Figure 2 – The priority cost reduction levers as tidal stream capacity is deployed, as devised by ETIP. [5]

research priorities evolving as capacity is deployed and the industry becomes fully commercialised.

The main challenge areas of focus were identified as follows:

- *Design and validation of devices*: The authors noted that testing and demonstration, particularly sea trials, are vital to improve reliability, reduce risk and reduce costs across the whole system, notably in marine operations. They also tout knowledge exchange as an important way to support technology deployment.

  Specific to tidal, they note that tidal blades and rotors are an important area of focus as a way to improve overall system reliability and performance, citing blade edge erosion and fatigue issues as particularly problematic.

- *Foundations, connections and mooring*: The authors note that there is learning that can be harnessed from other maritime industries, for example coastal defence, offshore wind and oil and gas. For floating devices, the key priorities are improving mooring systems and quick connection systems, both of which will improve the ease and speed of operations. For fixed devices, they identify installation as a key area for focus, as slack tide weather windows are typically small.
- *Marine operations*: Required actions in this category include the design of more advanced modelling tools (i.e. to simulate marine operations) and improving processes and monitoring systems to better understand operational working conditions and limits.
- *System integration*: Solutions in this category would see marine energy deployed at both larger utility scales, and also for niche applications as a way of demonstrating commercial viability and encouraging interest.

1.3. The TIGER Project

In 2019, the Interreg France (Channel) England Programme approved the biggest ever Interreg project. The TSE Industry Energiser Project, known as TIGER, is an ambitious €45.4m (~£38.76m) project, of which €29.9m (66%) comes from the European Regional Development Fund via the Interreg France (Channel) England Programme. It has been designed to be game-changing for the European TSE sector by bringing together leading tidal stream developers to collaborate and share best practice to accelerate deployment and provide evidence of cost reduction.

The TIGER project was launched in October 2019 and will be complete in June 2023. It falls within the funding category for low-carbon technologies, whose managing authority is Norfolk County Council. They co-fund collaborative projects between organisations in the south of the UK and the north of France.

The project is delivering new designs for improved performance and lower cost turbines, as well as associated infrastructure and ancillary equipment. It is establishing cross-border partnerships to develop new technologies, test and demonstrate them at a number of locations across the Channel region, and use the learning from this development to make a stronger, more cost-effective case to the UK and French Governments that tidal stream energy should be a part of the future energy mix.

The TIGER project will demonstrate that TSE is a maturing industry, capable of achieving an accelerated cost reduction pathway, and will position the Channel region at the heart of the sector by:

- Addressing technology challenges.
- Building the supply chain.

Figure 3 – The six tidal sites being supported within the TIGER project.

- Switching on new sites.
- Installing new turbines.
- The project aims to drive the growth of TSE by consenting 10+MW of new tidal capacity at sites in and around the Channel region, thus driving innovation and the development of new products and services. This will ultimately lead to the following:
- A reduction of greenhouse gas emissions (approximately 11,000 tonnes per annum).
- Investment in coastal communities, leading to an economic increase in GVA of €13m (~£11.1m) per annum.
- A tidal energy cost reduction towards the European target of €150/MWh (~£128/MWh).

The total theoretical TSE capacity in the Channel region is nearly 4 GW, enough to power up to three million homes. Proving that TSE generation can be cost-effective on a large scale could open the door for it to become the renewable energy of choice in coastal locations with strong tidal currents globally, helping the growth of clean, green energy production and tackling the climate emergency.

TIGER will make a stronger, more cost-effective case for TSE to become part of the energy mix in the UK and France by harnessing economies of scale via volume manufacturing and multi-device deployments. Coastal communities used as ports of deployment will benefit from knock-on investment and job creation.

Sites

Figure 3 shows the six tidal sites that are being supported through TIGER. These are located within or close to the Channel between the UK and France. A wide variety of potential site scales are covered: larger commercial sites (the Raz Blanchard, PTEC), -mid-scale sites (Morbihan Gulf, Ramsey Sound) and smaller sites for testing and demonstration (Paimpol-Bréhat, Yarmouth Harbour). The TIGER project activities, including companies and technologies to be deployed, are summarized in Table 1.

Table 1 – Tidal sites being supported through the TIGER project, including key partners and details on the technology to be deployed

Site	Key partners	Current status	Capacity to be installed	Technology to be installed	Timescale for deployment
Ramsey Sound	Cambrian Offshore SW	Recover turbine and install turbine	Up to 1MW	*TBC*	2022-23
Yarmouth Harbour	QED Naval	Site to be consented and turbines installed	up to 300kW	Community scale SubHub with 3x Tocardo T1 turbines	2022-23

Perpetuus Tidal Energy Centre (PTEC)	Orbital Marine Power, EMEC	New site, originally fully consented in 2016, currently going through re-consenting	30MW	Orbital O2 TBC	Deployment outside scope of TIGER (2025)
The Raz Blanchard	Normandie Hydroliennes	Site consent variation in progress, FEED	12MW	TBC likely SIMEC AR2000 series variant	Deployment outside of scope of TIGER (2024-25)
	Hydroquest	Site consent variation in progress, FEED	17 MW	Oceanquest next generation turbine	Deployment outside of scope of TIGER (2024-25)
Paimpol-Bréhat	EDF, SEENEOH, Hydroquest & EMEC	Deployed for testing and demonstration	1MW	Oceanquest 1 MW	Deployed (retrieval summer 2021)
	EDF, SEENEOH, BDI & Minesto	Deployed for testing and demonstration	100kW	DG100	2022
	EDF, SEENEOH & BDI	Test site to be repurposed	Various	*TBC*	*TBC*
Morbihan Gulf	Morbihan Hydro Energies SAS	New site to be consented	500kW	Sabella turbines *2x D08 250kW*	2022/23

1.4. Report structure

This report continues as follows:

Section 2 describes the study methodology, including data sources, choice of site (the Raz Blanchard), and choice of technology for the case study.

Section 3 describes the drivers examined and presents the individual LCOE impacts.

Section 4 presents the combined impact of all of the innovations together.

Section 5 presents the results in the context of the TIGER sites.

Section 6 summarises the findings and conclusions, suggesting recommendations to the industry and for future work.

2. Methodology

2.1. Choice of cost drivers

The study approach identified the various innovations and drivers that offer the potential for LCOE reduction in the tidal industry (henceforth referred to as "cost reduction drivers"). Then, using a bottom-up cost modelling tool, the shortlisted ideas had their potential LCOE impact estimated.

The first stage was to brainstorm all potential cost reduction methods and innovations. These were sourced from the following:

- Publicly available reports and news articles
- ORE Catapult expertise and knowledge, and
- Innovations and design improvements identified by TIGER partners.

Overall, 50 cost reduction drivers were identified. While the majority were TSE focused, some were identified from offshore wind studies and also deemed applicable for TSE (for example improvements in floating turbine mooring system design, condition monitoring of power cables).

This long list was reduced down to 20 innovations through a series of internal workshops and meetings. Innovations were selected based on the following criteria:

- Judged to have large cost reduction potential (for example impacting a costly part of the tidal stream device or project).
- Near to medium term potential: drivers judged to have a low impact before 2035 were removed (for example implementation of substations, as in this time frame most tidal farms will be close to shore).
- Less tangible drivers were removed, for example digital twin models, AI and machine learning improvements in reducing operational costs and improving reliability. While these will clearly be beneficial into the future, they are only in the early stages of being investigated for offshore wind, a more mature technology, and so the LCOE reduction benefits are difficult to quantify and expected to be some way off. Generally, these difficult to quantify drivers, without sufficient data, were removed.

These 20 drivers were shared with TIGER technical experts and were further reduced to eight final drivers to examine. These were expected to be the most significant from a cost reduction perspective and could also be modelled with the data available from TIGER partners and ORE Catapult cost models. A combined case considering the impact of both increasing turbine rotor diameter and rated power was added, hence the final drivers modelled were:

1. Increased rotor diameter of turbines
2. Increased rated power of turbines
3. Both increased rotor diameter and rated power (combining 1 and 2)
4. Subsea hub implementation
5. Improvements in wet mate connectors
6. Transition from gravity base to piled foundations
7. Improved blade materials
8. Larger farm size (improved economies of scale)
9. Lower weight average cost of capital (WACC)

All of the innovations are applicable to both fixed and floating device concepts.

2.2. Choice of site

The site chosen for the main analysis was the Raz Blanchard in Normandy, France. This is regarded as one of the most promising tidal stream sites in the whole of Europe, indeed the world, with previous studies indicating that it could support over 2GW of tidal stream capacity [7] [8]. Currently, as part of the TIGER project, two tidal projects are in the process of securing modified consents in the region:

1. Normandie Hydroliennes is a consortium made up of tidal turbine supplier Proteus Marine Renewables, AD Normandie and EFINOR. They took over a previous consent from ENGIE and are planning to install four 3MW devices by 2025 [9].
2. Hydroquest are a French tidal stream developer with a horizontal axis, utility-scale device concept. They are planning to deploy a 17.5MW array by 2025 [10].

Tidal flow speed data was provided by the University of Caen Normandy, who simulated the flow in Telemac. This data was a timeseries of flow speeds with fifteen-minute resolution. Within the Raz Blanchard, a high-flow location was chosen for the analysis. The specific location was chosen somewhat arbitrarily by calculating the annual energy production expected for the reference technology (as described in Section 2.3) across the data supplied and picking a point with a yield close to 6,000 MWh/year and suitable water depth (>38m).

Table 2 – Specifications of the site used for the study, in the Raz Blanchard, Normandy, France

Parameter	Unit	Value
Location	-	The Raz Blanchard, Normandy, France
Maximum spring tidal current (depth-averaged)	m/s	3.6

Water depth	m	38
Distance to construction/O&M port	km	30-40 (Cherbourg)
Distance to shore	km	5

2.3. Choice of technology

For the baseline analysis we chose a large, utility-scale device. This was deemed as most suitable for the reference site. While there are a multitude of smaller devices sub 1MW in development, suitable for shallower waters and alternative applications, utility-scale devices are widely regarded as the key for unlocking the full cost reduction potential of the technology. These generally have better material efficiencies, with larger components that can take advantage of economies of scale. Furthermore, the larger rotor diameters have larger swept areas and thus have the potential to capture more energy from the flow. The trend towards larger devices is generally considered to be the most significant factor in driving down LCOE for offshore wind (for example [11], [12]), and we also expect this to be the case for TSE (albeit to a lesser extent as rotor diameter is limited by the depth of water).

A horizontal axis rotor configuration was chosen as this is the dominant design choice, both in terms of devices currently installed and projects in the planning stages. This is expanded on further in Section 3.1.

For the baseline we decided on a four-device array. This is deemed representative for the current scale of the industry. Costs were devised assuming a farm installed in 2021. This hypothetical baseline scenario can be considered a reference point, the use of present-day cost estimates meaning that the impact of the individual cost drivers can be easily isolated.

We decided to consider a fixed bottom device rather than floating. This is because there are more of these device concepts being developed and it better matched the data that we had available. All of the innovations chosen are also relevant for floating devices, and we expect that the percentage reductions calculated are of a similar order.

Table 3 shows the properties of the tidal turbine chosen for the analysis. This was loosely based on a Proteus Marine Renewables AR2000 turbine[4], chosen for several reasons:

[4] Formerly developed by SIMEC Atlantis Energy. SIMEC Atlantis Energy sold a majority stake of their Advanced Tidal Engineering and Services division to Proteus Marine Renewables in October 2022.

- The design is established. The previous version, the 1.5MW AR1500, has been installed at Meygen for a number of years and hence represents a technology with real world commercial deployment.
- The design contains features that encapsulate aspects of the majority of device designs (horizontal axis turbine, utility-scale, fixed foundation).
- Data was readily available, as SIMEC Atlantis Energy were a partner on the TIGER project.

Table 3 – Reference device and farm chosen for the analysis.

Parameter	Unit	Value
Operating principle	-	Horizontal axis
Rated power	MW	2
Foundation type	-	Gravity base
Rotor diameter	m	20
Farm size	Units	4
	MW	8
Project lifetime	years	25
Discount rate	%	8
Commissioning year	-	2021
Currency	-	£ (2021)

2.4. Techno-economic modelling

A LCOE model was created to examine the impact of the cost reduction drivers on costs, energy production and ultimately LCOE. This allowed baseline values to be scaled up or down according to the improvements foreseen by the specific innovations. The model was created in Microsoft Excel, with a sheet created to examine each of the drivers. Note that the analysis is conducted in real terms £2021 currency.

The baseline scenario was created using existing cost data. These data were sourced from a variety of TIGER partners and combined with data from the ORE Catapult Analysis and Insights team to formulate representative costs for the tidal stream project. These sources can be summarised as follows:

- Turbine costs were obtained from several TIGER partners and scaled to estimate the device, as presented in Table 3.
- Development costs were assumed to be 3% of CAPEX, as was used for the ORE Catapult 2018 cost reduction study [13].
- Foundation costs were estimated using the ORE Catapult data from technology providers and scaled.
- Transmission system costs (subsea hub, export cable, onshore substation) were estimated using ORE Catapult cost models. These models have been developed over a number of years and are updated quarterly. They are primarily used to estimate costs and LCOE for the offshore wind industry and have been used in numerous publications (e.g. [13] [14]).

  The baseline scenario assumes each turbine is connected to the shore via individual export cables.
- Installation costs were obtained from TIGER partners.
- O&M costs were scaled from the ORE Catapult 2018 study [2] by taking account of data from TIGER partners and examining more recent 2020 costs incurred at Meygen [15].

The model estimates all project costs in 2021 real terms and outputs estimates of development expenditure (DEVEX), capital expenditure (CAPEX), operating expenditure (OPEX) and decommissioning expenditure (DECEX).

The energy yield was calculated using the equation [16]:

$$P = \frac{1}{2}\rho_W c_p A U^3 \quad (1)$$

where ρ_W is the density of seawater (1,023 kg/m^3), c_p is the power coefficient (assumed to be 0.41, e.g. in line with Meygen Phase 1A [15]), A the swept area and U the flow speed. This is the standard way to calculate tidal turbine power in the absence of a power curve.

The flow speed data that was provided was depth-averaged. This was converted to flow speed at turbine hub height, U_z, using the equation [17]:

$$U_z = \left(\frac{z}{h\beta}\right)^{\alpha} U \,,$$

where α is the shear coefficient (assumed to be 1/7), β is the roughness coefficient (assumed to be 0.3), h is the water depth and z is the hub height of the rotor above the seabed. This only had a marginal impact on the flow speed, increasing it by about 3% for the baseline scenario.

Output power was limited to the rated power of the turbine, P_r, i.e.

$$P_{out} = \min\left(\frac{1}{2}\rho_W c_p A V^3, P_r\right) \tag{2}$$

Table 4 – Annual energy production (AEP) and costs assumed for the project modelled in the study. All currencies are in £2021 except where noted.

Parameter	Unit	Value
AEP – gross	MWh/turbine/year	6,355
AEP – net		5,651
Capacity factor – gross	%	36.2
Capacity factor – net		32.2
CAPEX	£/MW	6,660,000
OPEX	£/MW/year	200,000
DECEX	£/MW	1,475,000
LCOE	£2021/MWh	305
	£2012/MWh[5]	239

Lastly, cut-in and cut-out flow speeds were applied. These were set at 0.5 m/s and 4 m/s, in line with data from TIGER partners.

3. Innovation Case Studies

This section describes the ten drivers that were chosen, including the LCOE reduction that was calculated.

3.1. Increasing rotor diameter

Description

Increasing the rotor diameter will result in an increase in energy yield because the increase in power generation scales approximately with the rotor squared, the larger

[5] Consistent with current base year for CfD strike prices.

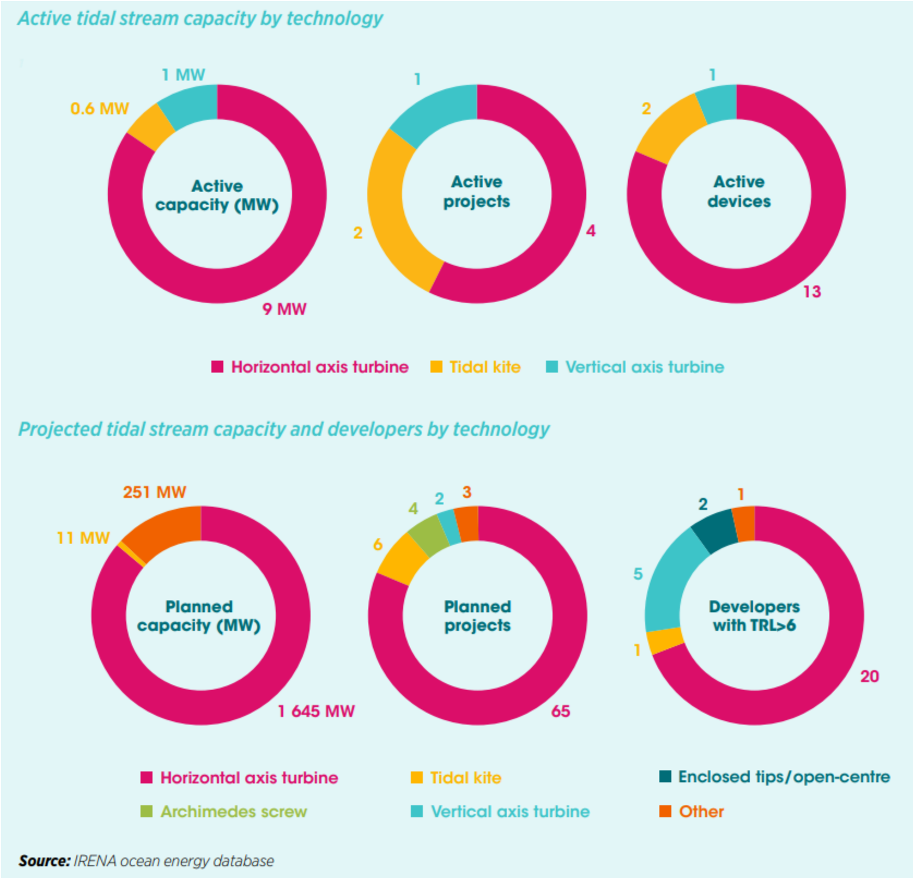


Figure 4 – Current and future pipeline of tidal projects by operating principle, as of 2020 [18].

swept area allowing more energy to be captured from the flow (see Equation (1). This can be applied to both floating and fixed devices.

Current materials/methods

The vast majority of tidal turbines have a horizontal axis configuration, as is the established design in wind energy. This is illustrated in Figure 4, taken from IRENA's innovation outlook on ocean energy technologies [18].

Table 5 shows typical rotor diameters and rated powers for a number of utility-scale devices. Rotor diameters have generally increased in size and performance. In 2008, the MCT Seagen device contained twin 16m rotors with a rated power of 1.2MW. This was followed by 18m, 1.5MW rotor diameters installed at the Meygen project in 2016. Modern utility-scale turbines, for example the Orbital Marine Power and Magallanes devices installed at EMEC in 2021, have rotors in the 20m range. The next generation of devices are expected to have rotors exceeding 24m.

Through the TIGER project we have engaged with a tidal blade manufacturer, who stated that rotors diameters up to 40m would be theoretically possible with their current machinery and approaches. As the industry gains traction, it is possible that established wind turbine blade suppliers like Vestas and LM Wind Power (a subsidiary of GE) could enter the market, which could significantly drive down costs and increase production capacities.

The maximum rotor size will be limited by the water depth at the site. The rotor will need clearance, both below the turbine and also above, the latter applicable to fixed-bottom devices to ensure that the turbine is not a navigational hazard (10-15m below lowest astronomical tide (LAT))

Table 5 – Utility scale tidal devices deployed or in development, with rotor diameters and rated powers. *Note that AR1500 IP now owned by Proteus Marine Renewables

Technology provider	Device	Nominal rotor diameter (m)	Rated power (MW)	Commissioning date
Orbital Marine Power	O2	21 (x2)	2 (2x1MW)	2021 (Fall of Warness, EMEC) [19]
Proteus Marine Renewables	AR2000	20-24	2	TBC (Meygen) [20]
Magallanes	ATIR	19 (x2)	2 (2x1MW)	2021 (Fall of Warness, EMEC) [21]
Andritz	Hydro Hammerfest HS1500	18	1.5	2016 (Meygen Phase 1A)
SIMEC Atlantis Energy	AR1500*	18	1.5	2016 (Meygen Phase 1A)
Sabella	D10-1000	10	1	2015 (Ushant Island, France) [22]
MCT	Seagen	16 (x2)	1.2 (2x0.6MW)	2008 (Strangford Lough) [23]

Modelling approach

We increased the rotor diameter from 20m to 26m, representing the next step change in rotor diameter envisioned for the next generation of utility-scale devices. This changed the AEP as calculated in Equation 1.

We scaled up the blade cost, approximately doubling it. This represents the additional material and manufacturing costs of producing the larger blades, and was derived by applying mass scaling relationships as have historically been seen in wind turbine blades [24]. We did assume a level of fixed cost in the blade manufacture, independent of the length (equal to 15% of the blade cost), as has been indicated by offshore wind developers on other ORE Catapult led projects.

We did not increase any other costs. The additional blade mass and thrust loads could result in increased costs in the powertrain and foundation, and the additional difficulty in handling blades could increase assembly and load out costs. We believe that these changes would be negligible relative to the total system cost and would require full conceptual and structural design to be properly estimated. For this reason, they were not included.

Impact on AEP, cost and LCOE

Table 6 shows the impact of the driver on AEP, costs and LCOE. The increased rotor diameter has a substantial benefit on AEP, increasing the energy capture per turbine by over 40%. This benefit is partially offset by the increase in blade cost, leading to an LCOE reduction of 24%.

Table 6 – Changes in AEP and costs for the increased rotor diameter innovation.

Parameter	Basis	Change from baseline
AEP per turbine (net)	per turbine	40.2%
CAPEX	per MW	8.9%
OPEX	per MW per year	0.0%
DECEX	per MW	0.0%
LCOE	per MWh	-24.1%

This is a large and accessible cost reduction driver. In reality, some system redesign would be required, and such long blades would also not be possible at all sites.

3.2. Increasing rated power

Description

Increasing the rated power for a specified rotor diameter can increase the energy that is produced, as the turbine generates more power at the rated flow speed. There will generally be an optimal rotor diameter/rated power pairing that will maximise annual energy production (AEP) for given flow conditions. For example, if the turbine generally operates well below its rated power then a smaller generator would make sense as this will be less costly. This would be indicated by a low capacity factor.

Increasing the rated power of a tidal turbine, independent of increasing rotor diameter, would lead to cost increases in the system due to the larger generator and higher rating of power electronics required. Both the cost and mass scaling are non-linear, meaning that larger devices of the same class will be more material-efficient and appear more favourable when looking at metrics like rated capacity per tonne.

Existing materials/methods

Table 5 shows the rated power of several well-known utility-scale device concepts. As previously mentioned, there has been a shift towards larger devices with greater rated powers to capture economies of scale. This is apparent when considering farms of a given capacity. For example, an 8MW farm made up of 1MW turbines would require eight devices to be installed and maintained, compared to only four devices if they were rated at 2MW.

Modelling approach

We considered a 3MW turbine, an increase in rated power of 50% compared to the baseline 2MW device. This is representative of the utility device scales currently being considered by companies such as Proteus and Orbital Marine Power.

We derived a new AEP using Equation 2, by limiting the power output to the 3MW rating.

For the turbine, data from developers indicates that there would only be a minor increase in mass (<5 tonnes) with a slightly heavier powertrain thus, we assume that there is no change in O&M, installation or DECEX cost per MW (as the same vessels could ultimately be used). We assumed a slight premium in powertrain cost, derived from cost scaling trends as previously published by Segura et al. [25].

Impact on AEP, cost and LCOE

Table 7 shows the impact of the driver on AEP, costs and LCOE. The 33.3% reduction in OEPX and DECEX represent the fact that, on a per turbine basis, the costs were assumed to remain the same.

Table 7 – Changes in AEP and costs for the increased device rating innovation.

Parameter	Basis	Change from baseline
AEP per turbine (net)	per turbine	5.5%
CAPEX	per MW	-32.9%
OPEX	per MW per year	-33.3%
DECEX	per MW	-33.3%
LCOE	per MWh	-4.7%

There is only a marginal increase in AEP. As for the larger rotor, this effect is site-specific, and we expect that there could be greater benefits at different sites.

The result is a decrease in LCOE of 4.7%. While overshadowed by the rotor diameter increase, this is still a substantial reduction and should be explored further, although again would require system redesign.

3.3. Combination of rotor diameter and rated power increases

Description

This is the result of combining both the increase in rotor diameter and rated power previously described in Sections 3.1 & 3.2. As mentioned, for a given flow speed profile there will be a combination of rotor diameter and rated capacity that will lead to the optimum energy production.

Existing materials/methods

A recent study, funded through the TIGER programme and carried out by the University of Plymouth, developed a numerical model to optimise rotor diameter and rated power for given site conditions [26]. This used cost functions, derived from the literature to optimise the levelized cost of energy for the turbine. The model was validated against publicly available data from the Meygen project. Preliminary findings indicated that optimising rotor diameter and rated power could reduce CAPEX per unit energy (i.e. CAPEX contribution to LCOE) by up to 40%.

Due to limited device deployments to date, such optimisations have not been seen in the field. It is anticipated that developers will generally try to maximise rotor diameter at sites, taking advantage of the previously mentioned cost scaling and performance benefits. Blade manufacture is still largely a manual process and involves creating blade moulds for the desired size. These moulds can take months to build, and the lowest cost and most widely used are typically only able to produce small numbers of blades (batches of 5-10 blades). Thus, it is likely that blade size would not vary significantly across a given project as this would have implications for blade cost and lead time. In the near to mid-term, we foresee developers having different classes of turbines with several standard blade size options, of which a single size would be used for a given project.

Modelling approach

We combined the 26m blade and 3MW rated power costs and properties, as previously discussed in Sections 3.1 and 3.2.

Impact on AEP, cost and LCOE

Table 8 shows the impact of the driver on AEP, costs and LCOE. The larger rotor increases the swept area of the turbine, hence increasing the energy that can be captured, and the rated power increase means that the turbine can generate more power at rated flow speeds.

Table 8 – Changes in AEP and costs for the combined rotor diameter and device rating increase innovation.

Parameter	Basis	Change from baseline
AEP per turbine (net)	per turbine	71.6%
CAPEX	per MW	-27.0%
OPEX	per MW per year	-33.3%
DECEX	per MW	-33.3%
LCOE	per MWh	-37.7%

This leads to a significant reduction in LCOE, which is greater than the two drivers when considered independently. The 38% LCOE reduction is somewhat idealised, as the additional O&M and structural requirements of the larger components could not be fully costed. Despite this, it is still an extremely large reduction and maps out the path for tidal technology to best achieve economic competitiveness with other forms of renewables. There are direct similarities with the way that offshore wind has been able to drive down LCOE so quickly, with increasing turbine size a key factor.

3.4. Subsea hub implementation

Description

Subsea hubs are used to connect arrays of tidal turbines to the mainland. Rather than running a subsea cable to shore for each turbine separately, which adds significant cost, the subsea hub is a junction box on the sea bed that combines the connections into a single export cable to shore.

This component is still in its infancy, with only one designed and deployed to date (by SIMEC Atlantis at Meygen). As a result, there are large cost reductions that could be realised, both through improved design and the supply chain, as the units are produced and deployed at sea in larger volumes. Moreover, in the future, it is also expected that more turbines could be connected into a single unit, reducing the number of subsea hubs and export cables required.

Existing materials/methods

For offshore wind, in the vast majority of cases, turbines are connected in strings to offshore substations. These collect and transmit power produced by each turbine to the mainland via a single cable route. This reduces costs as less cabling is required, and also allows voltages to be stepped up and hence transmission losses are reduced.

To date, tidal stream projects have seen turbines connected individually to the mainland. This approach has merits for small, early projects as it means that electrical system architecture design is simpler, and it is easier to isolate and carry out maintenance on individual turbines when faults occur. As the technology matures this becomes far less economically viable, especially for larger farms, as the supply and installation costs of cables become prohibitive. Offshore substations used in offshore wind are extremely costly and will not be required for typical TSE sites, which are within 5km of the shoreline.[6]

The middle ground for TSE is to use subsea hubs (or junction boxes) to connect small batches of devices (4 –10) into a central node. The combined power can then be brought to shore via a single export cable, reducing the supply and installation cost of the cabling required.

[6] Substations are more of interest for further from shore ocean currents sites.

A subsea hub's simplest function is to serve as an enclosure to protect multiple electrical connections. Within the marine environment, the means of protection on subsea hubs will be more complex than that of a typical junction box. Although there are a wide range of concepts that are submersible by design, hubs used in TSE applications currently stand at a very early stage of development. At present, applications for subsea hubs include O&G, marine equipment, submersible vehicles and hydroelectric generation [27].

Subsea hubs designed for used in TSE systems are in the early stages of development. SIMEC Atlantis Energy's Advanced Tidal Engineering and Services Division, now sold to Proteus Marine Renewables, have implemented their own subsea hub design[7]. This can connect up to four turbines to a single export cable. It also features wet mate connectors for individual turbine connection, a dry mate connector designed for the installation of an export cable, and an extra wet mate connector designed for the connection of an instrumentation sled. An illustration of the subsea hub is displayed in Figure 5.

Proteus Marine Renewables have indicated that the subsea hub will be improved for future projects. They plan to develop a next generation version that will contain a transformer within it so that loss minimisation can be achieved. However, with the addition of an internal transformer comes substantial additional weight to the new design.

[7] Proteus Marine Renewables acquired the IP from SIMEC Atlantis Energy in October 2022.

Subsea hubs are deemed less critical for floating concepts, as devices could be interconnected and daisy chained together within the hull of one of the devices [3]. This has not been achieved to date and will likely be explored for the next generation of floating arrays.

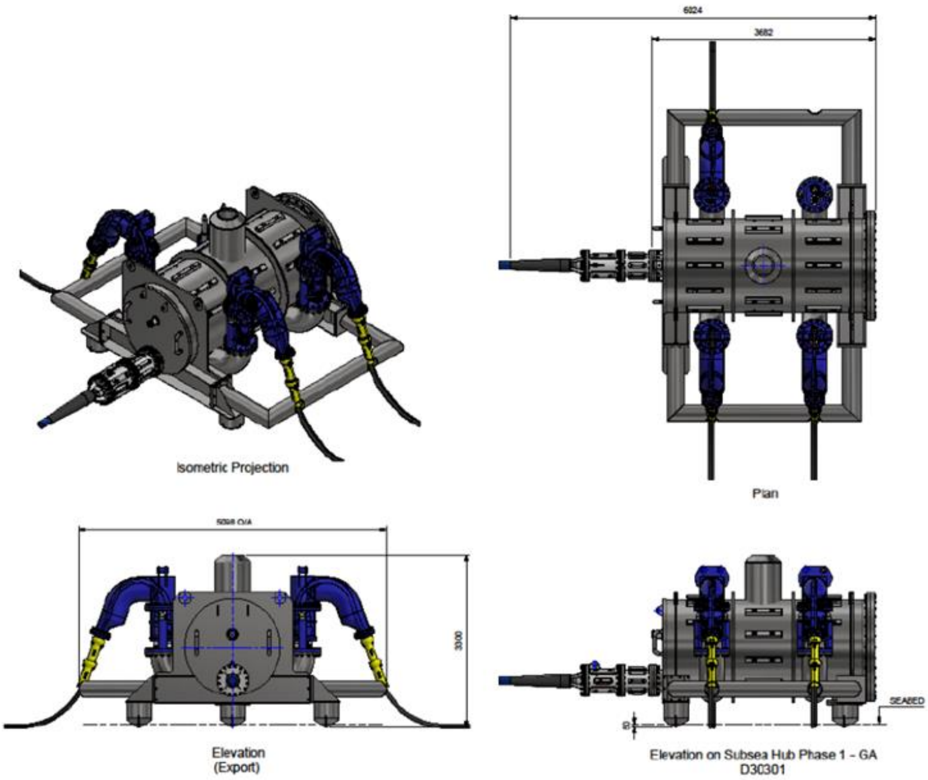


Figure 5 – SIMEC Atlantis subsea hub [28].

Modelling approach

In the baseline, we assumed that the four turbines are connected to shore individually. To examine the cost driver we included CAPEX and OPEX for a single subsea hub and assumed one export cable from the hub to shore (vs four previously). We also assumed additional costs for four 200m "inter-array cables" going from each turbine to the subsea hub.

Impact on AEP, cost and LCOE

Table 9 shows the impact of the driver on AEP, costs and LCOE. The CAPEX reduction is significant, attributed to the reduced number of cables that need to be supplied and installed.

Table 9 – Changes in AEP and costs for the improved subsea hub cost reduction driver.

Parameter	Basis	Change from baseline
AEP per turbine (net)	per turbine	0.0%
CAPEX	per MW	-11.1%
OPEX	per MW per year	0.0%
DECEX	per MW	0.0%
LCOE	per MWh	-8.0%

The overall benefit from subsea hubs would be more significant for farms further from shore, where cabling could be further reduced. Technology improvements could also reduce losses in the system which would further reduce LCOE, for example by installing converters within the subsea hub to transform the export power up to a higher voltage.

3.5. Standardization and upscaled manufacture of wet mates

Description

Wet mate connectors can be used to connect electrical cables to tidal turbines. These include the cables to extract power often with a fibre optic core that allow the device to be controlled and monitored. They allow the connection/disconnection to be made underwater.

Wet mate connectors are a long lead time item and tend to be quite expensive and bespoke for the tidal stream application. This is a point of focus to determine how improved design and reduced cost of wet mate connectors could reduce LCOE.

Existing materials/methods

As previously mentioned, the majority of tidal concepts are fully submerged and fixed to the seabed. Wet mate connectors allow connections to be made to the turbine underwater without having to recover the device and raise it above the water (as is the case for dry mate connectors). This is advantageous as it allows installation and O&M of turbines to be done more easily, quickly, and safely.

For larger farms, it is anticipated that subsea hubs will be required to interconnect turbines together to reduce cabling cost to shore (see Section 3.4 for a description of these). These hubs will be mounted on the seabed so that the export cable can be routed effectively to shore, thus wet mate connectors are also the preferred option.

Floating turbines may instead use dry mate connectors within the device hull, for example the Orbital O2 winches a "connector can" through a small moonpool where dry mate connectors are plugged into the turbine [28]. Thus, this driver is of less relevance for these devices.

There are a wide range of wet mate designs which are developed specifically for operation with tidal converters. More recent examples which secured funding in the Quick Connection Systems programme run by Wave Energy Scotland include:

- Nova Innovation's NovaCan which has been used alongside their M100-D turbines using cost-effective, off-the-shelf components [29].
- Quoceant's Q-Connect which consists of modular subsystems that can be assembled in different configurations to provide quick and safe electrical connection of wave and TSE devices [30].

These connectors are shown in Figure 6.

For TSE applications, wet mate connector designs are largely bespoke and, as a result, come at a high cost. Some attempts at standardisation have been made, for example MacArtney's 11kV (7.6MW) connector which was designed with the aim of producing a "low-cost, high voltage generic wet-mate connector" [31].

Through TIGER, technology providers and their suppliers have told us that wet mate connectors, while not the highest cost turbine components, are notoriously challenging to standardise. Different turbines have different power and control requirements, and existing suppliers are generally unwilling to design connectors for the tidal energy application as the industry is still at an early stage.

Tidal developers typically need to combine multiple connectors from catalogues together. These are uncommon connectors, so suppliers are reluctant to keep these in inventory as the overall demand for these products is low. This results in long lead times.

Modelling approach

Wet mate connectors are an active area of research, with different companies developing their own proprietary solutions designed for specific technologies.

We consider the case whereby improvements in wet mate connectors could lead to cost savings of 5% in the subsea hub and export cable, 25% cost reductions in marine operations (due to faster connect/disconnect and improved reliability) and a reduction of 25% in the connector costs within the turbine subsystem. We believe that these are reasonable cost reduction targets in the short to medium term, the large 25% reduction largely driven from buying in bulk and adopting more competitive tendering processes.

Impact on AEP, cost and LCOE

Table 10 shows the impact of the driver on AEP, costs and LCOE. The reductions in CAPEX and OPEX led to a LCOE reduction of 6.4%.

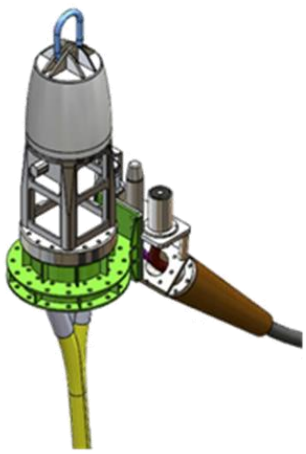


Figure 6 – Left: Nova Innovation's NovaCan connector [30]. Right: Quoceant Q-Connect connector [31].

Table 10 – Changes in AEP and costs for the wet mate connector improvement innovation

Parameter	Basis	Change from baseline
AEP per turbine (net)	per turbine	0.0%
CAPEX	per MW	-5.8%
OPEX	per MW per year	-9.4%
DECEX	per MW	0.0%
LCOE	per MWh	-6.4%

While not at the level of previous innovations, this is still impactful and an area that warrants further research and development.

The main benefits in improving these components would be from a lead time and supply chain perspective, as has been discussed in other TIGER deliverables (see Deliverable T2.2.2: Volume Manufacturing Roadmap [32]).

3.6. Transition to piled foundations

Description

Monopile foundations are the most common foundation choice for offshore wind farms, with 81% market share in Europe at the end of 2020 [33]. Their advantages include a relatively simple design, ease of manufacture, low cost and space efficiency, making it easier to transport multiple foundations on a single vessel and prepare them on the quayside prior to installation. Jacket foundations are the next most common, with 10% of the European market share at the end of 2020 [33]. These use more complex structure, secured via smaller pin piles, and are designed for deeper waters (approx. deeper than 40m).

Despite this, such piled foundations have seen little adoption in the tidal stream sector. Reasons for this include the fact that tidal sites tend to be rocky, hence such foundations would need to be drilled, which adds to installation time and cost. The low volumes currently required for the industry also mean that the full economies of scale cannot be utilised.

Foundation costs in offshore wind continue to come down. As the tidal industry grows, economies of volume will drive down the price of piled foundations, as offshore wind supply chains can be utilised more effectively (as suppliers will be willing to supply larger orders at better prices). It is anticipated that piled foundation will become dominant into the future. Studies have estimated that such piled foundations could reduce the mass of material by 90% [3], having a large benefit by allowing more foundations to be transported and installed by a given vessel, reducing the trips to and from site.

Existing materials/methods

Currently gravity base foundations are the preferred choice for fixed-bottom devices. This is because these are well understood and easy to design, and are more straightforward to install at tidal sites because foundations can be lowered onto the seabed without the need for drilling. Developers will usually wait for slack water or neap tides to install these turbine foundations, and suitable weather windows can be short. Examples of turbines installed with these types of foundations include:

- The four 1.5MW turbines at Meygen (250-350 tonne foundation with 1,200 tonnes of ballast blocks [34])
- Sabella's 1MW D10 device that was deployed at Ushant Island in 2016 had a foundation weighing approximately 450 tonnes [35]

While the foundations vary in shape and mass, they usually consist of a core steel structure and concrete or steel ballast.

Floating devices have also been deployed using gravity base foundations (gravity anchors), for example the Orbital Marine Power O2 device that was installed at EMEC in summer 2021. The company have suggested that scrap material could be used as ballast for the gravity anchor, reducing cost and promoting sustainability through the reuse of materials [36].

There have been tidal devices installed on monopiles. Among the most well-known were:

- Marine Current Turbines (MCT) Seagen device, a 1.2MW twin rotor device. The rotors were mounted on a frame, attached to a 3m diameter central monopile [37], and could be raised out of the water for maintenance. This was installed at Strangford Lough in 2008.
- The OpenHydro "open-centre turbine" was installed on a twin monopile foundation at EMEC in 2007 [38]. This was the first tidal turbine installed at EMEC, with the foundation allowing the turbine to be lifted out of the water for maintenance (in much the same way as the Seagen device). Later OpenHydro device concepts employed gravity bases, for example the array planned in the the Raz Blanchard, France [39], and the failed demonstrator installed in the Bay of Fundy [40].

The key purpose for the monopile for both these concepts was to allow easy access of the device for maintenance, important as tidal stream technology was in a very early stage of development and without the knowledge and improved reliability seen today. As a result, these monopiles were very large and surface piercing, and would not be so economic for current device concepts which are targeting smaller footprints and lower costs by being able to reduce extraneous mass.

Future designs will use much smaller piles, taking advantage of offshore wind supply chains. Such steel piles will likely require drilling into the seabed; this is because tidal sites tend to be rocky, with sediment washed away by the tidal currents. This involves the use of either an individual drill piece or a drilling tool inserted into the pile. To ensure an adequate fit is made, alignment tools are used and grout is laid between the hole and pile foundation. Often a self-supporting hold or "socket" will be pre-drilled which the pile is then grouted into.

Modelling approach

We assumed a cost reduction in foundation supply of 75% from going from a gravity base to a monopile foundation. This was informed by data from partners and in line with previous studies [2]. We increased the installation cost by 16% to account for the need for drilling and hence longer installation times required.

This assumes a commercially ready foundation, which we expect will be seen into the late 2020s as larger arrays are deployed. We expect that monopile projects could be seen in the mid to late 2020s, for example at the Raz Blanchard (Normandie Hydroliennes and Hydroquest) or in the UK AR4 CfD projects. These will give a good early indication of cost competitiveness and viability.

In reality, we believe that there could be a slight cost increase in the development stage, as geophysical surveys of the seabed will be needed for pile design, however this would be relatively small and site-specific and so has not been included. The O&M and inspections associated with piles we expect would be similar to gravity base, so this cost has also not been altered. Lastly, while in some jurisdictions there is a need to fully remove piles from the seabed, leaving the seabed as it was before installation, this is not commonplace. The piles could most likely be trimmed off, leaving the pile in the ground. This would add some cost in the decommissioning stage, however this would be insignificant when considering the wider projects costs, and would also be heavily discounted into the future as per the LCOE calculation methodology.

Impact on AEP, cost and LCOE

Table 11 shows the impact of the driver on AEP, costs and LCOE. A 3.4% LCOE reduction is significant, and warrants further investigation. The length and thickness of piles will be very dependent on the device type and site, and so this benefit could vary quite significantly (up to ±50%).

We expect that this magnitude of improvement could also be seen for floating devices going from gravity anchors to drag embedment or piled anchors, albeit to a lesser extent (as some of the foundation system cost is also in the mooring lines and connectors).

Table 11 – Changes in AEP and costs for the piled foundation cost reduction driver.

Parameter	Basis	Change from baseline
AEP per turbine (net)	per turbine	0.0%
CAPEX	per MW	-4.8%
OPEX	per MW per year	0.0%

DECEX	per MW	0.0%
LCOE	per MWh	-3.4%

3.7. Advanced blade materials

Description

The blades are a crucial component of tidal turbines. While the sizes of the rotors can vary, as discussed in Section 3.1, in all cases they need to be carefully designed to ensure high operating performance and survivability.

This cost reduction driver examines potential cost reductions in blades from using novel materials. One example is thermo-plastic blades. These materials could allow blades to be manufactured using additive, 3D printing methods. The blades can also be recycled or reused much more easily, as the plastic polymer can be heated up to a liquid and remoulded. While the materials are currently more expensive, studies have suggested that these materials could reduce wind turbine blade costs by 10% and reduce production cycle time by 15% as the technology improves and becomes widely adopted [41]. The cost reductions are complimented by reduced energy and labour requirements [42].

Thermoplastics blades are being tested on one of the turbines on Verdant Power's New York East River device [43]. This is a collaboration between the tidal technology developer and National Renewable Energy Laboratory (NREL). While the blades are currently short, at 5m length, the aim is to test these and potentially scale them up to 10-15m for future device classes

Technical experts working on TIGER have spoken to technology developers regarding future blade concepts, who indicate that cost savings of up to 75% could be possible.

Existing materials/methods

Tidal blades are generally manufactured from composites, typically glass fibre-reinforced plastic (GRP). Learning has been taken from the offshore wind industry, for example regarding materials, simulation methods and blade shape, although the production volumes and blade sizes are much smaller. Typically blades are designed to be thin, which improves the hydrodynamic performance and leads to improved energy production [44]. Water ingress can be a problem, as the blades are submerged, which can lower the fatigue lifetime by 1-3 years [45]. This is an ongoing area of research and could change the materials and blade properties that are used for future technology.

Other materials that have been demonstrated include metal blades (typically steel), however these become too heavy at larger sizes, and carbon fibre, however this is more expensive [46] and particularly difficult to recycle [47].

Modelling approach

We assumed a reduction in blade CAPEX of 50%. This is within the range (10-75%) that has been indicated by current research.

We kept the O&M cost the same. This was for two main reasons:

1. Due to lack of operating experience in the sector, the proportion of O&M attributed to the blades is difficult to ascertain and is likely to vary greatly between different blade sizes, designs and site conditions (e.g. turbulence and unsteady flow).

2. The impact of new blade materials on blade integrity and lifetime is an ongoing area of research, with uncertainty due to limited testing to date.

We expect that O&M would reduce in the real world, as developers are unlikely to settle for materials with degraded structural performance in the field. As research in this area improves, the wider implications will be better understood.

We also did not consider any uplift in AEP due to the new blade materials, as any benefit is still largely unknown.

Impact on AEP, cost and LCOE

Table 12 shows the impact of the driver on AEP, costs and LCOE. The 50% blade cost reduction leads to a 4.2% reduction in the total CAPEX and 3.0% in overall LCOE. This highlights the fact that blades are a significant part of the device CAPEX and warrant further research.

This estimate is somewhat conservative because O&M benefits have not been included. There are also wider environmental benefits, for example thermoplastic blades could be recycled which benefits a circular economy.

Table 12 – Changes in AEP and costs for the improved blade materials innovation.

Parameter	Basis	Change from baseline
AEP per turbine (net)	per turbine	0.0%
CAPEX	per MW	-4.2%
OPEX	per MW per year	0.0%
DECEX	per MW	0.0%
LCOE	per MWh	-3.0%

3.8. Increase in farm size

Description

Deploying larger farms, made up of more devices, is an important way to create step-change reductions in LCOE. This is through increased economies of volume, through cost savings associated with buying components in bulk. Through TIGER, tidal technology providers have indicated that cost savings on some components could be as high as 50% if procuring for larger arrays of 20 devices (compared to the concept designs primarily deployed to date). Other costs that scale favourably with farm size include:

- Installation and O&M: The fixed costs of mobilising and demobilising the vessel are spread over a greater number of turbines.
- Development: The increased size of the lease area does not increase the associated cost in a linear way (the development and consenting activities would still be done by a similar number of people over a similar timeframe).
- Onshore transmission: Onshore substations will be required for array-scale farms. For farms up to a few hundred megawatts we expect that one substation would be sufficient. The costs of onshore transmission cabling, substation installation and onshore civil works would remain very similar, with a small difference due to the differences in electrical equipment required.

Larger farms will also lead to a more adept and confident supply chain. Some suppliers are apprehensive about providing and keeping small batches of fairly bespoke components in their inventory if there is not a clear growing market being demonstrated. Deployment of larger farms will lead to more favourable conditions for the tidal technology developers and increase competition in the supply chain, ultimately driving down costs.

A larger farm, with more turbines in the water, would cause more drag in the tidal flow, with turbines suffering reduced production through wake effects. There could be the ability to mitigate this through clever turbine arrangement, to take advantage of constructive interference effects. This is an ongoing area of research, e.g. [48] [49].

Existing materials/methods

Currently within the UK there are two tidal turbine arrays:

1. The Shetland Array was the first grid-connected tidal stream array in the world, when two devices were installed in 2016.

   The Shetland Array is operated by Nova Innovation, containing four of their M100 devices. Each device is rated at 100kW. The latest device was installed in October 2020, and there are plans to install two more devices; this is being funded within the €20m EnFAIT project[8].

2. SIMEC Atlantis own and operate a 6MW four device array, Meygen Phase 1A. This is located in the Pentland Firth between Orkney and the Scottish mainland. It consists of four 1.5MW devices (three Andritz Hydro Hammerfest and one

[8] EnFAIT – Enabling Future Arrays in Tidal (accessed 11/10/2022)

Atlantis AR1500) and generates revenue via the Renewables Obligation (RO)[9] with a contract for 5 Renewables Obligation Certificates (ROCs) per MWh produced.

Both of these are small in relative terms when compared to the sizes of more mature offshore wind arrays, where arrays of 100+ turbines are not uncommon. While the tidal resource is different, with sites typically more constrained by geography such as channel width, the ambition is to deploy farms on similar scales to fully harness the cost savings and efficiencies.

Modelling approach

We modelled a 100MW farm of 50 devices, each rated at 2MW. We assumed that there would be cost savings across most device components, as the larger economies of scale could secure more favourable prices from suppliers. We judged this to be 15% across most turbine components, equal to the cost reductions ORE Catapult see for offshore wind projects.

For the installation of the device and foundation we calculated a reduction of 60% in the per MW cost. This assumes a heavy lift DP vessel at £150k per day is used for the installation, with 10 days required for mobilisation and demobilisation and a 20% premium added to account for waiting for weather windows. The main cost reduction comes from the fact that the mobilisation and demobilisation costs are incurred once in both cases (£900k total), spread across a higher installed capacity (£112.5k/MW for the 8MW farm reducing to £9/MW for the larger 100MW farm).

For O&M we calculated reductions of 60% for planned inspections and 8% for unplanned major and minor repairs, calculated using a dedicated Microsoft Excel model. We assumed that all of the devices would be inspected in a single, annual campaign. This means that, as for installation, mobilisation costs are spread across more devices. The unplanned maintenance only sees a slight improvement, occurring due to the fact that it becomes cheaper to charter the main O&M vessel on a long-term basis rather than having to mobilise each time there is a failure (which is the preferred approach for the smaller farm). We assumed that minor repairs could be done using a large multicat-type workboat, with major repairs requiring a heavy lift DP vessel.

The onshore electrical system accounts for a third of the LCOE reduction. This is because fixed costs of the onshore export cabling and substation are spread over the larger number of devices (we assumed a single substation would be required for both the 100MW and 8MW farms).

For the AEP, we assumed that all devices see the same incident flow, as the farm is hypothetical and deriving a layout would require detailed technical analysis outside the

[9] Precursor to the CfD.

scope of this work. We reduced the availability loss by 20% to reflect logistical efficiencies from operating a larger farm (for example more optimal vessel usage). We increased wake losses from 3% to 15%. This number is subject to larger uncertainty, as in reality it depends on the flow conditions and array layout.

Impact on AEP, cost and LCOE

Table 13 shows the impact of the driver on AEP, costs and LCOE. The result is over 28% LCOE reduction, with substantial cost reduction spread across CAPEX, OPEX and DECEX.

The AEP decrease is due to the assumed wake losses. This is an indicative figure, and in reality will vary depending on the specific farm layout, flow regime and sizes of turbine. As learning improves, we expect that this figure could reduce, and will benefit from verification in the field as the next generation of arrays are deployed as a result of UK CfD AR4.

Some of the other cost reduction drivers in this study are relatively "quick wins", with focus on specific components which could be achieved through targeted R&D (for example grant funding). This driver, on the other hand, would require large capital investment: potentially hundreds of millions of pounds. It would certainly require some form of revenue support and private sector investment. Hence, we think that this driver will not be seen until late into the 2020s (or possibly early 2030s) once the technology has been appropriately de-risked and demonstrated at small array scales (<10 turbines).

Table 13 – Changes in AEP and costs for the 100MW farm cost reduction driver.

Parameter	Units	Change from baseline
AEP per turbine (net)	per turbine	-11.4%
CAPEX	per MW	-33.1%
OPEX	per MW per year	-42.1%
DECEX	per MW	-60.0%
LCOE	per MWh	-28.4%

3.9. Reduction in Weighted Average Cost of Capital

Description

To date, the tidal stream industry has only seen small numbers of devices installed. While the technology has been proven, it has not been deployed at a significant commercial scale. As the technology is deployed at larger volumes, reliability and performance will improve and lead to a de-risking of the technology. This will improve the financing available to tidal stream technology and project developers, for example giving them access to debt financing from commercial lenders at lower interest rates (such as corporate bonds). Moreover, investors will settle for a lower cost of equity as projects are able to demonstrate sustained revenues and cash flows. These drivers will reduce the weighted cost of capital (WACC) secured for projects and reduce the effective levelized cost of the project.

Existing materials/methods

In the tidal stream sector, a large amount of funding has come through public sector grants to complement the significant private investments made. In the UK and France, EU grants have traditionally made up much of this, with some recent and ongoing projects shown in Table 14. However, often these projects will require some level of match funding from the private sector.

Table 14 - Examples of current tidal stream government funded projects that are ongoing. [1]Funded through the European Regional Development Fund (ERDF). [2]Funded through the Horizon 2020 programme.

Project/scheme	Total amount	Timeframe	Funding body	Tidal technology developers	Themes
TIGER [50]	€45.4M	2019-23	EU[1] (€30M)	Hydroquest, Minesto, Orbital Marine Power (OMP), Proteus Marine Renewables, QED Naval, Sabella	• Deploying technology • Improving supply chain • Cost reduction
FORWARD-2030 [51]	€26.7	2021-25	EU[2] (€20.5M)	OMP	• Deploying technology • Hydrogen production • Volume manufacturing
EnFAIT [52]	€20M	2017-22	EU[2] (€14.9M)	Nova Innovation	• Array layouts and wake interactions
Carbo4Power [53]	€7.8M	2020-2024	EU[2] (€7M)	Sabella	• Rotor blade materials
SELKIE [54]	€5.2M	2020-2023	EU1	None	• Software tools
ELEMENT [55]	€5M	2019-22	EU[2]	Nova Innovation	• Control systems • AI
Saltire Tidal Energy Challenge Fund [56]	£3.4M	2019	UK (Scottish Government)	OMP	• Deploying technology
OPIN [57]	€2.6M	2018-22	EU[1] (€1.5M)	None	• Creating industry networks

VOLT [55]	£2M	2021-23	UK (Scottish Government)	Nova Innovation	• Volume manufacturing
EVOLVE [58]	€1M	2021-23	EU[2]	OMP	• Energy system impact

Some tidal developers have had notable success with equity crowdfunding, including:

- Orbital Marine Power secured £1M in crowdfunding in less than a week in 2020 [59]. The campaign was hosted on Crowdcube, with over £2M raised at the end of the campaign, with the company giving away 5.41% in equity [60].
- Nova Innovation: Campaigns have included a 2019 campaign, whereby the company raised £1.1M (£500k originally targeted) [61], and more recently in 2021, where the company raised over £2M on Seedrs platform (£1M originally targeted) [62].
- QED Naval: The company raised over £1M in March 2021, on Seedrs crowdfunding platform, from an initial target of £350k [63]. The final offering was 7.69% equity.

Some firms have also secured debt financing by issuing bonds:

- SIMEC Atlantis Energy raised £3.79M by issuing a bond on the Abundance crowdfunding platform in 2020, at an 8% interest rate and reaching maturity in 2024 [64]. This followed a £4.95M raise in 2017, via two bonds.
- Orbital Marine Power raised £7M in 2019, also via the Abundance platform. This was the largest amount raised on the platform at the time. Debentures of 2-5 year duration were offered, at interest rates of up to 12% [65].

Lastly, there are two tidal stream companies who are publicly listed:

- SIMEC Atlantis Energy – London Stock Exchange (AIM)
- Minesto – Stockholm Stock Exchange

The majority of private funding to date has been through equity. As the industry is largely pre-commercial, companies are not generating sustained cash flows, and hence taking on significant debt is problematic as companies have less ability to make interest payments. Banks and other lenders are also risk adverse, and the type of construction risk present in the marine environment is a barrier to securing favourable loan conditions. Many lenders currently view the technology as too risky, especially given the high upfront CAPEX and long payback periods [66], but this will change as tidal farms demonstrate sustained operating activity on larger scales.

Offshore wind has seen a considerable inflow of capital in the last five to ten years, as the technology has become de-risked and lenders are assured consistent returns. This has been helped through market mechanisms like the CfD which ensures a consistent revenue stream within the wholesale market. A considerable influence has been in the increase in debt financing for the construction phase, which has driven down WACC significantly [67]. Ocean Energy Europe have stated that a 30-40% reduction in project costs could be possible if project developers were able to secure interest rates at similar levels to offshore wind [68].

Modelling approach

We modelled a 20% reduction in WACC, from 8% to 6.4%. This could be expected into the mid 2030s as the technology demonstrates commercial viability at larger array scales and can utilise lower interest debt financing.

Impact on AEP, cost and LCOE

Table 15 shows the impact of the driver on AEP, costs and LCOE. A 20% reduction in WACC results in a 10% reduction in LCOE. This is a significant amount, and will be achieved as the technology scales up to larger arrays and as the sector is able to attract more private investment.

Table 15 – Changes in AEP and costs (in real £2021 terms) for the decreased WACC cost reduction driver.

Parameter	Basis	Change from baseline
AEP per turbine (net)	per turbine	0.0%
CAPEX	per MW	0.0%
OPEX	per MW per year	0.0%
DECEX	per MW	0.0%
LCOE	per MWh	-9.6%

4. Combined Impact of Innovations

Figure 7 shows the cumulative impact of applying all of the cost reduction factors. Both the individual and combined impact of the rotor and rated power increases are shown. Below the x-axis we also show the individual % LCOE reductions for each innovation.

We found that the combined innovations could reduce LCOE reduction by 67.5%. For our baseline scenario, this would take the LCOE down to £99/MWh (£78/MWh in £2012). The majority of these innovations (to the left of the 100MW farm) could be achieved by the time the AR4 CfD projects are expected to be installed (by 2026-28), equivalent to an LCOE reduction of 50%. With the exception of advanced blade materials, it is likely that these will be present to some degree on the next generation of arrays deployed for AR4.

We expect the first 100MW farm to be deployed by 2032, assuming that tidal stream continues to have access to revenue support via CfD. In 2022, the government recently announced a change to the CfD mechanism: holding auctions annually rather than every two years, as has been seen historically. This gives the tidal stream industry flexibility, and also regular opportunities to demonstrate this cost reduction trajectory through the CfDs that are awarded.

The situation in France is less clear, as the government is yet to announce formal revenue support. As of February 2022, discussions are in place regarding a power purchase agreement (PPA). Two projects are being developed in the Raz Blanchard totalling 29MW: by Hydroquest (17MW) and Normandie Hydroliennes (12MW). If the consent variations are granted then these will be installed by 2025/26 and could form the basis of larger 100MW+ arrays by 2030.

Our LCOE estimation of £86/MWh (£2012) for the first seven innovations (up to and including the 100MW farm) exceeds the previous ORE Catapult study, which predicted approximately £130/MWh after 200MW of cumulative deployment. We have only included the main drivers as we judged them, so we expect that there is an increased opportunity for cost reduction below this level through other aspects. These include items such as supply chain improvements (including increased competition), improvements in O&M procedures through "learning by doing", and reductions in insurance premiums as technology is demonstrated and de-risked. The most significant of these drivers are described in Appendix A:.

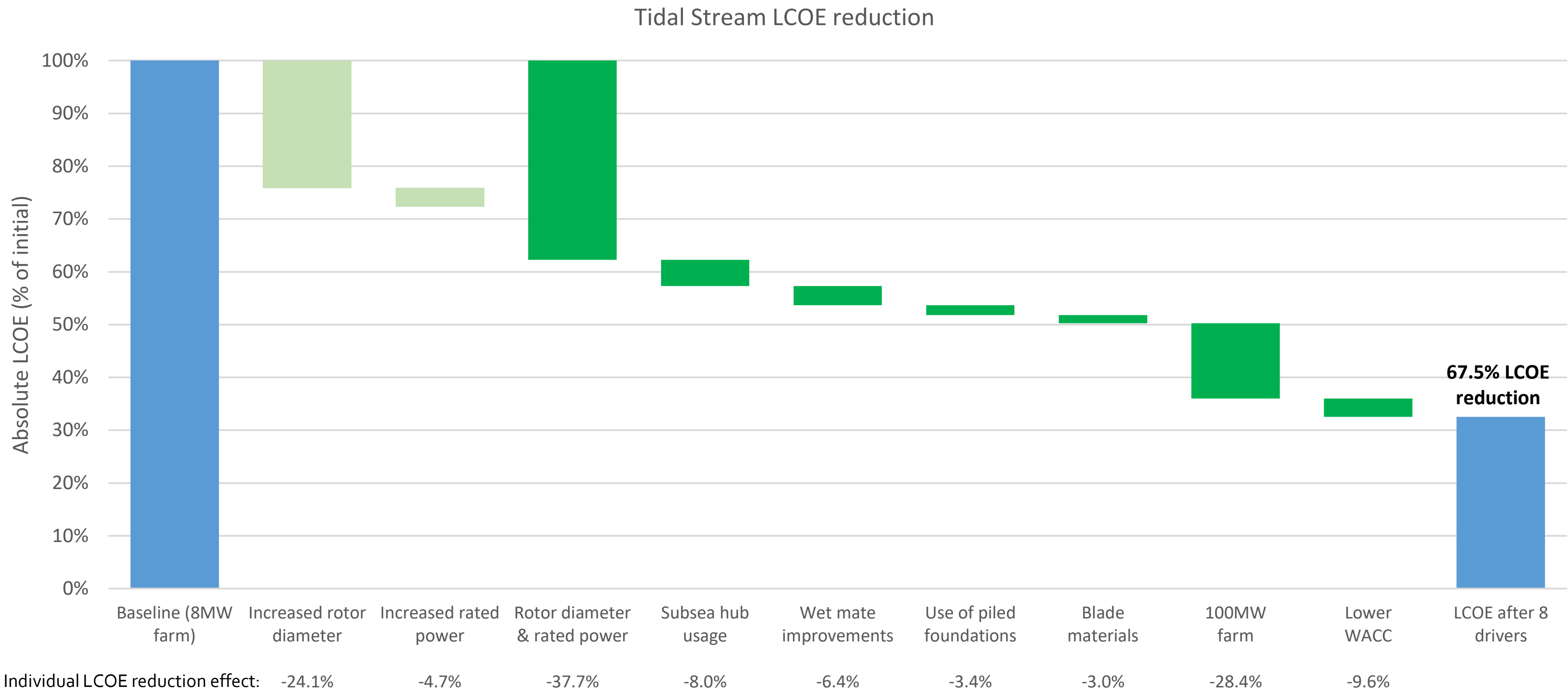


Figure 7 – LCOE reduction that can be achieved by the cost reduction drivers examined. The increased rotor diameter and rated power represents the additive nature of the two previous innovations (in lighter green).

5. Innovations in context of TIGER Sites

The TIGER project is progressing tidal projects at six European locations, shown in Figure 8. Table 16 summarises the suitability of the six sites for the cost reduction drivers examined in Section 3. Green indicates highly suitable drivers, orange drivers that are generally suited and red drivers that are deemed less suitable.

Table 16 – The suitability of the six TIGER sites for implementing the cost reduction drivers. Green (H): highly suitable. Orange (S): suitable. Red (L): less suitable

Driver	The Raz Blanchard	Isle of Wight	Morbihan Gulf	Ramsay Sound	Paimpol-Bréhat
Larger devices (rotor diameter & rated power)	H	H	L	S	L
Subsea hubs	H	H	S	S	L
Wet mate connectors	H	H	H	S	S
Piled foundations	H	H	S	S	S
Advanced Blade materials	S	S	H	H	H
Large farms	H	H	S	L	L
Lower WACC	H	H	S	L	L

Figure 8 – Tidal stream project locations being developed as part of the TIGER project.

5.1. Larger commercial sites

The Raz Blanchard and Isle of Wight have the ability to become large commercial sites. There is scope for farms of 100MW+, which will reduce costs through economies of volume and also allow WACC to be reduced through debt financing.

These sites span relatively large areas. Depths are well suited for large rotor devices to unlock large cost reduction.

We think that testing innovations such as advanced blade materials should be de-prioritised for sites at these locations, given the relatively low benefits compared to upscaling devices and farm sizes. Using proven, existing blade materials could also be easier for manufacturing, allowing devices to be manufactured and deployed more quickly.

Suitable areas in the vicinity of the Isle of Wight are typically close to shore (e.g. PTEC is within 2km) and so we think there is less cost benefit to be gained from subsea hub usage. Within the area there are a good variety of sites: with two commercial scales sites in development (PTEC and Portland Bill) and a test site under development near Yarmouth Harbour (see Table 1).

5.2. Smaller commercial sites and test sites

Morbihan Gulf is a smaller commercial site. Within the wider Brittany region there could be tens or perhaps hundreds of MW of capacity, so there could be some cost benefits from economies of volume. This could particularly be the case if established device designs are productised and rolled out across the region.

The area is a hotspot of leisure activity, including tourism and recreational usage (for example diving and water sports). This, combined with fairly shallow waters, means that larger rotor devices are unlikely to be suitable as the devices will need to be out of the way of other sea users. This could also be the case for monopiles, which could cause some disruption during installation. We also think that floating devices will be less suitable, as they can present navigational hazards, so wet mate connectors will be or interest and could unlock cost reduction.

As for the Isle of Wight, suitable areas tend to be close to shore, with smaller devices and cables anticipated, so subsea hubs would be less of a requirement.

Ramsey Sound and Paimpol-Bréhat are smaller-scale sites. As such, we believe that they would be unable to fully unlock the cost reduction benefits from larger economies of scale.

Paimpol-Bréhat, owned by EDF and operated by SEENEOH, is a test site and there are no plans for commercial array deployment. We think that it would be best suited as an area to test emerging technologies (for example blade materials, condition monitoring and measurement systems, novel foundations, marine operations, performance and power curve verification, etc).

While Ramsey Sound itself is a fairly small area of seabed, there is potential for larger-scale arrays in the vicinity (for example St David’s Head, where company TEL were planning to install a 10MW array). The seabed is known to be rocky and uneven, and there is an 80m deep channel within the sound. This gives uneven, fluctuating flow conditions [69], which could make the area a good testbed for tidal blades and other components susceptible to tidal loading fatigue.

6. Conclusions and recommendations

6.1. Conclusions

In this study we have introduced the most cutting-edge innovations and cost reduction drivers currently being researched for tidal stream energy. Starting from over 50 specific cost reduction drivers, we narrowed this down to the eight deemed most significant via a series of internal workshops.

For these, we quantified the LCOE reduction that could be unlocked should the drivers be commercially adopted. We did this by first building an LCOE model in Microsoft Excel. We modelled a baseline farm of four, 2MW devices, assuming a horizontal axis, bottom fixed technology commissioned in 2021. We then varied individual parameters by considering the cost and performance improvements that could be attributed to each cost reduction driver. These improvement factors were estimated from the literature, from trends seen in offshore wind, and using data from TIGER project partners.

The result was that we were able to quantify the LCOE reduction associated with each driver (and the combined impact of the increased rotor diameter and rated power turbine). We were able to compare and discuss each of these in the context of the wider industry, and provided examples of the current state of the art and the research that is ongoing.

We found that the combination of the increased rotor diameter and rated power provided the largest LCOE reduction, estimated at 38%. This innovation is site-specific, as shallower sites will limit the size of the rotor that can be deployed. The majority of the improvement comes from the increase in rotor diameter, rather than the increase in power. We also found the increase in farm size to be very significant, with a 100MW farm reducing LCOE by 28%. This excluded the effect of reduced WACC which was considered separately. In reality, a larger farm would enable better financing arrangements and more favourable conditions from lenders, and so this impact would likely be greater than modelled.

Some of the more minor drivers included wet mate connector improvements (6.4% LCOE reduction), advanced blade materials (3.0% LCOE reduction) and piled foundations (3.4% LCOE reduction). We found that the combination of the eight individual innovations (including the combined benefits of increased rotor diameter and rated power) could reduce LCOE by 67.5% compared to the baseline, present day device.

We discussed the cost reduction drivers in the context of the TIGER sites. We expect that the most significant cost reduction can be unlocked at the larger and deeper sites: namely the Raz Blanchard and the Isle of Wight. This is because there is space for larger farms (100MW+) and the water is deep enough for large rotor devices. Morbihan Gulf is shallower and there is more overlap with other sea users, therefore would benefit more from specific technology innovations: for example wet mate connectors and advanced blade materials, which could be demonstrated on smaller devices. Ramsey Sound and Paimpol-Bréhat are small-scale sites, better suited for testing, and therefore would be good places to test, at scale, innovations which could then be applied to larger farms at more commercial locations (e.g. subsea hubs, blade materials, control strategies, logistical procedures).

We also introduced a longer list of innovations that could benefit tidal stream. The LCOE benefit of these was quantified as part of the study, mainly because of lack of data and the fact that many are expected to occur much further into the future. These included coating and corrosion management, novel anchors (e.g. rock bolts), mooring system improvements for floating devices, increasing use of robotics and AI (for example for O&M and logistical planning) and purpose built vessels for the sector.

6.2. Further work

There are several ways that this study could be built upon into the future:

- The study could be expanded to consider other types of baseline devices (e.g. floating, small fixed devices <500kW). While we believe that the results are representative of the tidal industry as a whole, there will be some differences as there are differences in specific cost areas and performance.
- The LCOE model could be designed with more site specific calculations built into it, allowing the waterfall chart to be presented for specific locations and considering different technologies. This would require more input from site operators and technology developers to obtain the necessary cost data.
- Some of the drivers examined have impacts beyond just LCOE. These include increased employment opportunities, improved gross value add (GVA) for regional economies and lower CO_2 emissions over the product lifecycle. Future work could quantify these impacts too.
- The study could be expanded to consider other tidal stream applications: for example hydrogen production and desalination. Such applications will have a role to play in decarbonising the wider economy, and will have their own specific cost reduction pathways that could be explored. This would allow the best synergies between tidal and these systems to be determined.
- This study was largely focused on cost reduction drivers that could be harnessed in the short to near term (per 2035). There were many innovations considered

but some were deemed to be too far into the future and has a lack of data to make an assessment (e.g. AI and robotics, purpose built vessels). These could be incorporated into a future study as understanding improves.

- This study does give context to the chosen innovations, including current research. The research investment cost to bring the innovations to market is not quantified, and could be factored into a future study. The grant funding required in different areas was estimated in the ETIP Ocean study [5], as summarised in Section 1.2. Future work could build on this by drilling down into specific innovations, including discussions with technology developers to understand their financial needs.

6.3. Final summary and recommendations

This study has quantified the LCOE reduction that eight specific innovations[10] could unlock for the tidal sector. The result is a 67.5% LCOE reduction, which would help to make the industry more cost-competitive with other renewables and build the foundation for a strong and vibrant industry. The gives the industry a target and helps to make the economic case, which will help tidal stream energy become a success in the UK and France: providing energy security and meaningful contribution to net-zero targets.

From the knowledge gained and conclusions of this study, we recommend the following actions to the industry to help these cost reductions become a reality:

Blade design

- This study identified increased rotor diameter to be a leading cost reduction driver. We believe that this should be explored in greater detail, to fully understand the cost implications and material properties of larger blades.
- There are several test facilities capable of testing large tidal turbine blades, for example the ORE Catapult blade 50m test rig and the University of Edinburgh's FastBlade facility. Such testing (for example accelerated life fatigue testing) could be combined with economic considerations, bringing in suppliers like A C Marine and Composites, to determine the feasibility of such large blades, and improve on the LCOE reduction estimate. This would also include a detailed analysis of maintenance tasks and impacts on downtime and blade failures.

Cost monitoring framework

- Technology developers can be apprehensive about sharing the data needed for techno-economic modelling, even under NDA. This is understandable, as these companies are keen to keep a competitive edge. We argue that some form of

[10] Nine including the combined impact of larger rotor diameter and larger rated power which were considered together as an additional driver

sharing of cost data is crucial for the industry to become a success, and more transparency is needed to be able to demonstrate that progress is being made. Independent third-party verification is also important, as it makes the industry more credible and mitigates the danger of companies “over promising and under delivering” on economic viability, which has been seen in the past.

- We believe that some form of cost monitoring/cost sharing framework is important to ensure that cost reduction is being demonstrated, as this is a major concern of the government. This could take the form of the offshore wind cost reduction monitoring framework. This was coordinated by ORE Catapult and ran between 2013 and 2018, creating a credible, government supported, framework to judge industry progress and specific innovation improvements. This type of arrangement does, however, require a critical mass of projects, to ensure that cost data can be aggregated to an industry level without the risk of being able to back-calculate confidential individual project costs.

Financial drivers

- The study was mainly focused on technological drivers, however, the 10% reduction in LCOE for a 20% reduction in WACC was significant.
- More can be done to advise companies on how to access different types of funding: for example blended financing approaches, green bonds, access to debt, raising equity through e.g. crowdfunding and angel investment.
- Device decommissioning bonds and insurance are also barriers, which the industry struggles to secure at reasonable rates due to a lack of general operating experience in the sector. As part of TIGER a study was conducted into suitable insurance models for the sector and a pilot is being planned to create a protected cell company (PCC) captive insurer as a structure to overcome the failure of the insurance market to provide sufficiently robust insurance products to enable new ocean energy projects to be demonstrated and commercially deployed.
- We recommend that policymakers work with technology developers to understand the financial landscape that they are operating under, as improvements in how projects and companies are financed could have significant implications for LCOE reduction without the need for e.g. large R&D grant funding.

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Appendix A: Extended Innovation List

Here we outline other innovations which were identified during this project. These were either judged to have a limited impact on the sector, were deemed not realistically achievable in the mind to long term (before 2035) or had less direct benefit for LCOE reduction.

Descriptions of leading innovations

Whole System

- **Coatings and corrosion management**
    - Novel coatings, such as thermal spray aluminium are being developed by the offshore wind industry to reduce manufacturing time and inspection/maintenance requirements. These are also applicable to the tidal stream industry.
    - The thermal spray aluminium method developed by Ramboll involves spraying molten aluminium onto the monopile before sealing it with a synthetic resin. This fully replaces the need for sacrificial anodes being applied to monopiles. The Arkona windfarm project was the first to apply this method and was fully commissioned in 2019 [70] [71].
    - Such novel coatings are coatings are most beneficial for the foundation and main device structure, which tend to be metal (floating device hull or fixed device tower and nacelle).
    - There have been novel coatings examined to mitigate biofouling, for example silicone coatings for blades and copper coatings for components like heat exchangers [72]. Anti-fouling coatings can be broadly categorised as chemically active antifouling paints or non-stick release coatings [73]. A recent project investigating biofouling is the NEMMO project, where solutions like gel-coat coatings [74] and innovation micro-textures that mimic fish scales [75] are being used to inform biofouling solutions.

Substructure

- Rock bolts anchors for large scale floating tidal
    - These anchors have been trialled by companies such as Sustainable Marine [76] and McLaughlin & Harvey & SeaRoc [77].
    - Sustainable Marine's Swift anchor is being explored for other applications, such as aquaculture, and has advantages including a significantly reduced carbon footprint, low profile and environmental impact and a short installation time of 30 minutes in slack tides [78].

    - Potential LCOE reduction. Move away from gravity anchors to lower CAPEX/DECEX solution installed with drilling rig and low cost workboat vessels.

  - The Tetraspar floating wind design utilises primarily bolt and pin connections for its substructure similar to the wind turbine, meaning better modularity and a simplified adaptability to current logistic methods of the wind sector [79]. Such connections could also be utilised for tidal devices to allow quick connection/disconnection from the mooring system

Mooring Lines

- Many of the ideas and innovations recorded for mooring lines originated or are being investigated in floating offshore wind. They could also have potential in the tidal industry depending on the device concept.

  - **Different connector designs**

    - Use of dampers/load reduction devices or quick connection systems could potentially allow the use of:

      - Shorter chain lengths
      - Smaller chain diameter requirements
      - Reduce the need for additional redundancy
      - Reduced connection time

  - **Switch from catenary configurations to a semi-taut design**

    - Enables a reduction in mooring line length, and hence cost.

  - **Use of new materials**

    - Improved nylon designs or more advanced synthetic designs. These will lower the mass of the system, making it easier to handle and allowing smaller and lower cost vessels to be used for installation. They are also resistant to corrosion and can demonstrate better performance (for example reduced bending fatigue [80].

    - Develop more “robust” materials which don’t have to be handled with such care which can lead to delays in installation, double handling etc.

    - Altering material/design to reduce biofouling.

    - New synthetic mooring solutions are currently being investigated by Ideol and Bridon-Bekaert Ropes Group who teamed up to develop innovative mooring solutions for floating offshore wind [81]. Another example is floating foundation supplier Principle Power, who teamed up with Dyneema and used their Lankhorst mooring tether on the WindFloat Atlantic project [82]. Dyneema claim that their DM20 rope has a 30% smaller diameter than polyester rope and is 70% lighter [83].

Anchors

- **3D printed anchors**
    - Could be either concrete or additive manufacturing of steel
    - Less material required
    - Potential for lower cost anchors. Concrete suction anchors, once fully commercialised could reduce manufacturing costs by an estimated 75% compared to steel anchors and LCOE by 1.2-2.1% for a 1GW floating wind farm [84].
    - Potential of reduced space requirements and the option of manufacturing them at port.
    - An example company currently looking to achieve this is RCAM Technologies which have been awarded multiple funding packages to further their 3D printed concrete anchor manufacturing design [85].

Transmission

- **Substation for tidal**
    - Tidal stream projects are typically close to shore (within 5km), exploiting tidal flows focussed by natural features like channels between islands and tidal flows around headlands.
    - As discussed in Section 3.4, subsea hubs are the industry’s preferred solution for transmissions and to reduce the cabling required.
    - As projects get larger and further from shore (e.g. devices targeting ocean currents), offshore substations could be a lower cost alternative: as a way to reduce cabling cost, reduce the installation and O&M associated with lots of subsea hubs and allow power to be exported at higher voltages, reducing transmission losses.

Installation and O&M

- **Increase use of robotics**
    - Due to more adverse site conditions, autonomous systems may become a valuable solution to increase weather window time but also reduce the time required to conduct surveys or O&M. The possibility of fully remote

surveys will also reduce the risk and cost of having a manned vessel offshore.

  - An example of current unmanned surface vessel designs which are receiving investments are the iXblue and the DriX. The DriX USV has the capabilities to sail for seven days at seven knots or more than ten days at a reduced speed [86].
  - Wind energy inspection is being made increasingly easier through use of drones, e.g. for blade inspection. There are also novel robotic solutions being trialled, for example the BladeBug robot which assists technicians with inspection and repair [87]. It is possible that such technologies could be used for tidal stream, particularly devices with surface piecing elements.

- **Improvement on mooring installation process**
  - Installation devices which can simplify and speed up the process either through different connection designs or optimised tensioning systems
  - An example of one of these systems is the STEVTENSIONER which is basically a chain shortening clutch with the mooring chain connected on one side and a reaction chain running through it. This can make the installation an easier and cheaper process [88].
- **Improving load out process**
  - Reduce load out time or reduce/remove requirement for barges or other plant equipment
  - Wetmate connectors at the right voltages/ quick release systems
  - Enable the use of ROVs to disconnect turbine
  - An example of these quick release systems would be from Apollo's PALM connector which uses a passive locking mechanism to act as the connection and load transfer between the WEC and mooring system [89].
- **Vessel ownership**
  - When speaking to tidal technology developers as part of the TIGER project, many stated their desire to own and operate their own vessels as a way to reduce project costs.
  - While some developers own and operate small workboats to assist with operations, none own the larger vessels that are required for installation or O&M

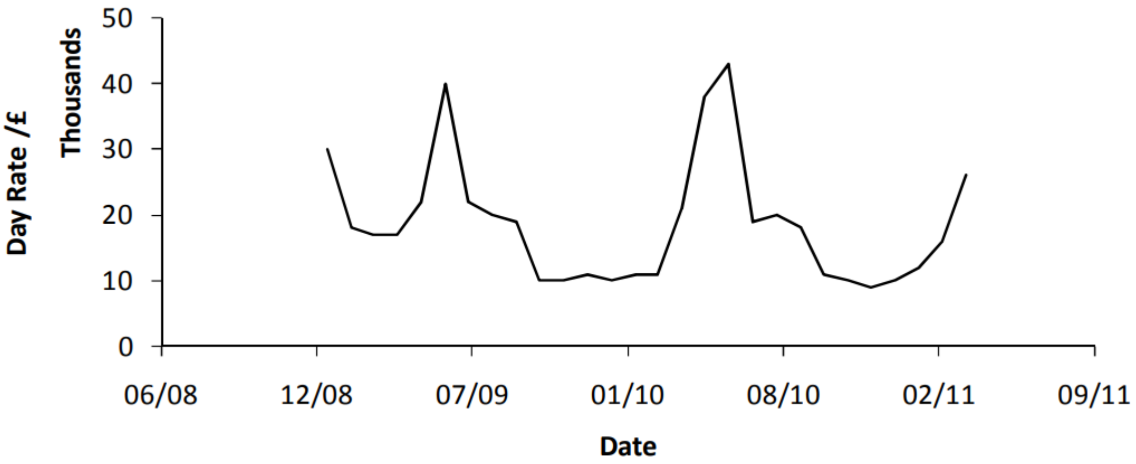

Figure 9 – Example anchor handling tug day rates [92].

- Typical vessel charter rates can be expensive, especially for larger vessels such as jack-up vessels that have been used for installing utility scale devices on the seabed. For example, studies have suggested that vessel charter can account for 70% of lifetime OPEX for offshore wind [90]. By owning their own vessel, developers would only need to pay for fuel consumed, labour and maintenance of the vessel, reducing cost for marine operations.

- Spot prices for vessels can vary significantly, depending on availability, seasonality and oil price [91] [92], on the order of ±50%. An example of this is shown in Figure 9. As well as the possibility of high costs, the uncertainty is also problematic as this makes the future cash flows associated with projects more uncertain and therefore more risky to investors who prefer consistent returns.

- **Purpose-built vessels for tidal stream**

  - The offshore wind industry is finding that vessel supply is becoming increasingly constrained, with difficulty in keeping up with demand.

Figure 10 – The "High Flow 4" (HF4), a vessel concept designed by Mojo Maritime (now James Fisher) for supporting tidal stream projects [101].

- Tidal stream typically uses vessels from the oil and gas industry, where available. These are not designed for tidal turbine installation, for example stable operation in extreme tidal currents. Vessels with dynamic positioning (DP) capability can be used, but there are typically expensive.

- Some companies have explored the possibility of purpose-built vessels designed for tidal stream. For example, in 2014 Mojo Maritime (now James Fisher) presented a concept design for a catamaran with a 250 tonne lifting capacity, designed to support the full tidal farm lifecycle (including foundation installation, turbine installation, cable lay and decommissioning) [93]. A visualisation of this is shown in Figure 10, but it ultimately failed to progress as the industry failed to progress as fast as anticipated.

- The advantage of such vessels would be that they would be designed specifically for typical tidal turbine dimensions and masses, meaning that they could be designed to be smaller and better able to operate in extreme tidal environments.

Other Innovations

These innovations are generally less tangible and more relevant for offshore wind/specific TSE technologies.

Innovation	Component	Description
Use of shared anchors - suction buckets or piles	Anchors	Reduce number of anchors required at the site
New materials	Anchors	Develop more "robust" materials which don't have to be handled with such care which can lead to delays in installation, double handling etc
Optimised disconnection system with mooring lines and cable at single disconnection point	Dynamic Cables	Reduce time of disconnection during O&M.
Splice box	Dynamic Cables	A splice box which connects two dynamic array cables and allows them to be wet-stored on the seabed when a turbine is towed to port. This allows the array to continue operating when one device is removed.

Cable design	Export Cable	Tidal stream device cables are estimated to represent 13% of the CAPEX costs [94]. Recent research demonstrates that a rocky seabed can have a wide fluid boundary layer and high seabed friction, due to the ruggedness. The observed stability of the export cables used at MeyGen, which could not be certified as stable using the conventional design approach, supports this [95].
Mooring monitoring and inspection	Mooring Lines	A load monitoring system to identify stresses on mooring lines and when maintenance is needed. The monitoring system will be integrated into an existing spring, which also acts as a dampener on mooring lines, and is powered by movement of the lines
Sea/ship simulator	O&M	An immersive simulation suite that will transform approaches to offshore decommissioning and renewable energy infrastructure projects in the North Sea has been launched in the north-east of Scotland [96]. This offers a risk-free way of testing O&M procedures.
Machine Learning	O&M	Advancements in onboard data logging systems, combined with machine learning techniques, unlock the potential to predict fouling effects accurately and determine when cleaning is required.
Digital twins	O&M	Utilising a digital twin can offer an approach to reduce the uncertainty in reliability prediction. Validated design tools are one of the key needs for achieving a market-competitive levelized cost of energy (LCOE).

O&M onsite access optimisation	O&M	Optimised O&M strategy will balance preventative and reactive maintenance to minimise downtime (maximise AEP) while keeping total OPEX low.
Increase hub/tower height off seabed	Rotor	Flow speeds are greatest around the free surface and least at the seabed. Increasing the hub height of fixed foundation designs would increase their energy yield.
Multi rotor systems	Rotor	Using constructive interference to boost power production, taking advantage of local blockage, etc
Optimised pitch controller for mean and rated speed	Rotor	Taking state of the art technology from wind sector and adapting it to wave/tidal devices
Condition monitoring software	Substructure (Floating)	Condition monitoring software which uses readily available acceleration and motion data points from a floating wave/tidal device to extrapolate how the wider structure responds to stress. This is originally for floating offshore wind but could also be applied to the wave and tidal sector.
Roll stability optimisation	Substructure (Floating)	Minimise platform roll to enable larger rotor diameters
Nacelle structure mass reduction	Turbine	Using recorded data from design to reduce the nacelle mass as it is likely overengineered
Optimised braking system	Turbine	Removal of the high-speed mechanical shaft brake, therefore reducing CAPEX and maintenance requirements
Nacelle structure optimisations for access	Turbine (Floating)	Increase freeboard for onsite access, in-water swapping of nacelles. Plug and Play ability could benefit floating devices as it can reduce downtime.

Leg lifting actuation optimisation	Whole system	Will enable larger rotors for floating Orbital Marine Power O2 device. Plug and play modularity.
Leg design improvement for lower CAPEX	Whole system	Reduces mass and enables lower cost manufacturing approach for floating Orbital Marine Power O2 device.
Casting design	Whole system	Use castings as alternatives to complex steel fabrications.
Design for system redundancy	Whole system	Potentially increased CAPEX to introduce further system redundancy to reduce OPEX and AEP losses due to O&M interventions over the lifetime of the project. Equally, there could be system aspects that could be removed to save cost, where the extra redundancy is not required. One example could be the number of mooring lines for a floating device. In general, the key will be to design the full system from a cost perspective.
Inventory control	Whole system	The management of spare parts has been utilised in other industries but could also be applied to offshore renewables. A study over a 10-year period in the aerospace industry showed a 30% reduction in unscheduled downtime, 20% reduction in the value of spare parts and a 30% improvement in spare part availability [97].

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