CATAPULT
Offshore Renewable Energy

TIDAL STREAM TECHNOLOGY ROADMAP


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ACRONYMS

Acronym	Description
AIF	Axial Induction Factor
AR4	Allocation Round 4
AR5	Allocation Round 5
AR6	Allocation Round 6
AR7	Allocation Round 7
CfD	Contract for Difference
CM	Condition Monitoring
CRL	Commercial Readiness Level
DAS	Distributed Acoustic Sensor
DTS	Distributed Temperature Sensing
EMEC	European Marine Energy Centre
GVA	Gross Value Added
HSE	Health, Safety, and Environmental
IPC	Individual Pitch Control
LCoE	Levelised Cost of Electricity
MEC	Marine Energy Council
MPPT	Maximum Power Point Tracking
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OMP	Orbital Marine Power
ORE Catapult	Offshore Renewable Energy Catapult
OWGP	Offshore Wind Growth Partnership
OWIH	Offshore Wind Innovation Hub
R&D	Research and Development
PCC	Protected Cell Company
TRL	Technology Readiness Level
TS	Tidal Stream
WACC	Weighted Average Cost of Capital

EXECUTIVE SUMMARY

This report covers tidal stream (TS) cost reduction via technology innovation and demonstrates how cost reduction is crucial in enabling an accelerated growth trajectory for the sector. The focus here is on innovations which will be needed to achieve ~1GW of installed TS capacity in the UK by 2035 as per recommendations put forward by the Marine Energy Council (MEC). With the UK grid becoming ever more dependent on variable renewable generation, grid balancing costs have risen substantially in recent years, with the cost of balancing the UK's power grid coming to £4.19bn in 2022, an increase of 250% since 2019 [1]. Such a drastic rise in grid balancing costs highlights the criticality of futureproofing the UK energy system through increased flexibility and a diverse portfolio of predictable low-carbon generation - of which TS can significantly contribute towards - thus driving the need for industry support and technology commercialisation.

To support the transition to a low-cost, decarbonised energy system TS can play a role in reducing UK energy system dispatch costs by £100-£600m per annum by 2050. However, achieving savings in the upper end of this estimate depends on the cost reduction trajectory that is achieved across the coming decades, which will also influence the installed TS capacity deemed optimal for the UK energy system [2]. To allow TS to play a role in the net zero revolution, technology innovation is key to improving yield and reliability while reducing capital and operating costs. Previous work done as part of the TIGER project indicated that just eight drivers alone can play a role in reducing TS's levelised cost of electricity (LCoE) by 67.5%, with six of these being technological as shown in Figure 1 [3].

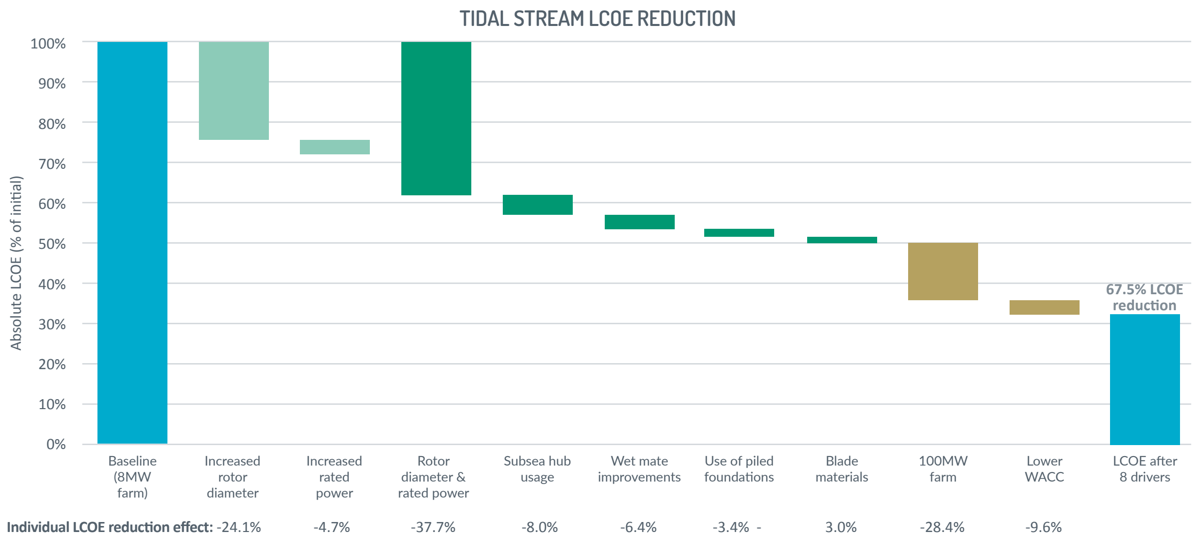

Figure 1: LCoE reduction of 67.5% that can be achieved by eight cost reduction drivers. Rotor diameter & rated power represents the additive nature of the two previous innovations (highlighted in light green). 100MW farm and Lower WACC are economic drivers (highlighted in gold) [3]

THE NEED FOR TECHNOLOGY INNOVATION

The following report builds on the findings of the T3.4.1 Cost reduction pathway of tidal stream energy in the UK and France report to give a comprehensive overview of the current status and challenges associated with what are expected to be the ten most impactful pre-commercial innovation areas in terms of their individual impact on TS LCoE. As well as this, the technology readiness level (TRL), commercial readiness level (CRL), case for intervention to enable commercialisation, and the health, safety, and environmental (HSE) impact of each innovation area are also considered. Estimates on LCoE reduction were attained through a combination of internal modelling and external stakeholder engagement which involved TS technology developers, supply chain, and academia. Below in Table 1, the TS LCoE reduction which is achievable by each innovation area is shown.

Innovation Area	LCoE Reduction Range (%)
Step Change in Rotor Diameters	20+
Subsea Hubs	10-20
Array Optimisation to Minimise LCoE	10-20
Innovative Anchoring Solutions for Floating Devices	5-15
Step Change in Rated Generator Power	5-10
Controllers that Optimise Lifetime Turbine Performance	5-10
Optimised Foundations for Fixed Devices	5-10
Optimising and Standardising Wet Mate Connectors	2-5
Condition Monitoring of Cables	2-5
Individual Pitch Control	2-5

Table 1: Tidal stream LCoE reduction of each innovation area

By using the results in Table 1, the LCoE trajectory of TS was then estimated out to 2035 under three cost reduction scenarios: conservative, optimistic, and mid-range. These scenarios are dependent on the degree of impact that cost reduction via technology innovation has based on the cost reduction ranges seen for each innovation area in Table 1. The results of each scenario are shown in Figure 2 which assume timely and sufficient research and development (R&D) funding is made available to deliver innovation commercialisation. It should be noted that projections here assess the cost reduction impact of technology innovation in isolation up until Allocation Round 7 (AR7) before the effects of a range of non-technical cost reduction enablers are realised post-2030, with these enablers explained in greater detail in Section 2.3.

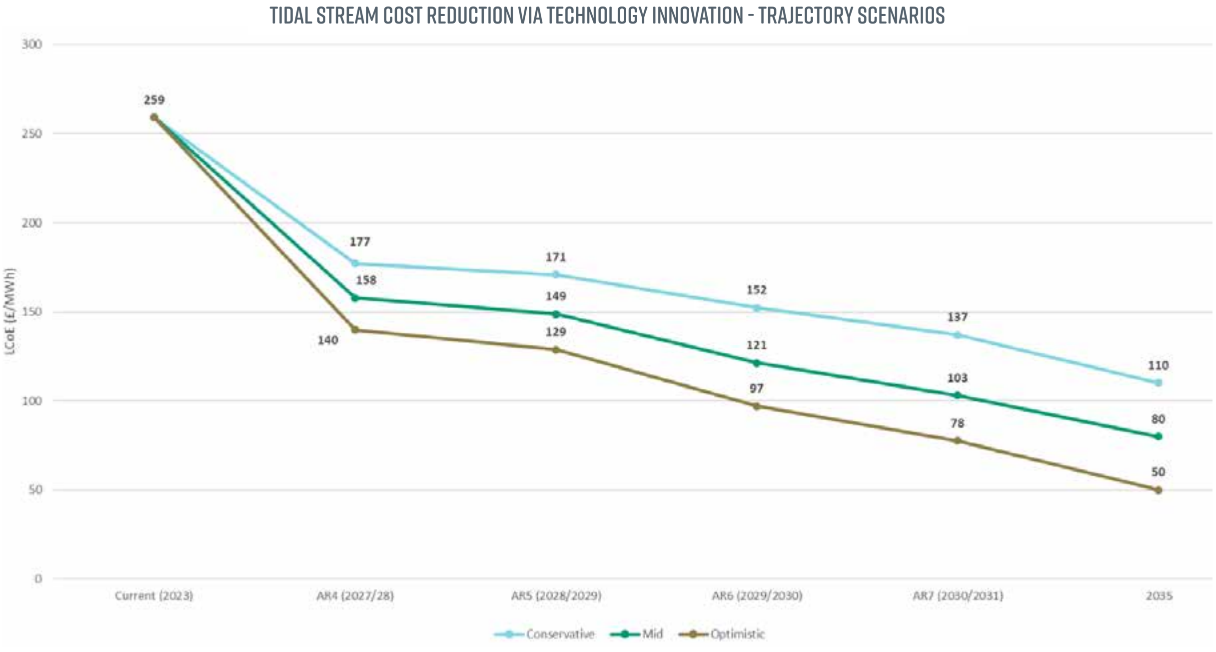

Figure 2: Tidal stream cost reduction trajectories

THE NEED FOR CHANGES TO CONTRACTS FOR DIFFERENCE

Under the current auction process, the amount of capacity that is awarded for a given technology at each Contracts for Difference (CfD) allocation round is dependent on the strike price reached, and the amount of funding secured within the pot that a given technology finds itself competing in. As a result, this structure favours projects that can deliver at the lowest strike price. However, with TS having had £10m/year of ringfenced support for Allocation Round 5 (AR5), and £20m/year for Allocation Round 4 (AR4), the industry was guaranteed to have CfDs awarded to a number of projects despite them meeting a higher strike price than other technologies in the same auction pot. Looking forward, without continued ringfenced support which is sized in step with TS cost reduction, future levels of TS deployment will not grow sufficiently to achieve ~1GW by 2035. Beyond ringfencing, recognition of non-price factors such as system integration and supply chain development in the CfD allocation process would be one way of levelling the playing field for TS to ensure greater deployment levels in the coming decades.

Regardless, technology cost reduction is crucial under any CfD mechanism in the short-term to maintain government support. This highlights the need for R&D funding in key innovation areas which will increase the amount of long-term capacity that can be won by TS under a reformed CfD allocation process. Most importantly, government should act swiftly in implementing non-price factors, with delayed action having a significant impact on the TS capacity that is installed by 2040 under both optimistic and mid-range cost reduction scenarios. The impact of this is illustrated in Figure 3.

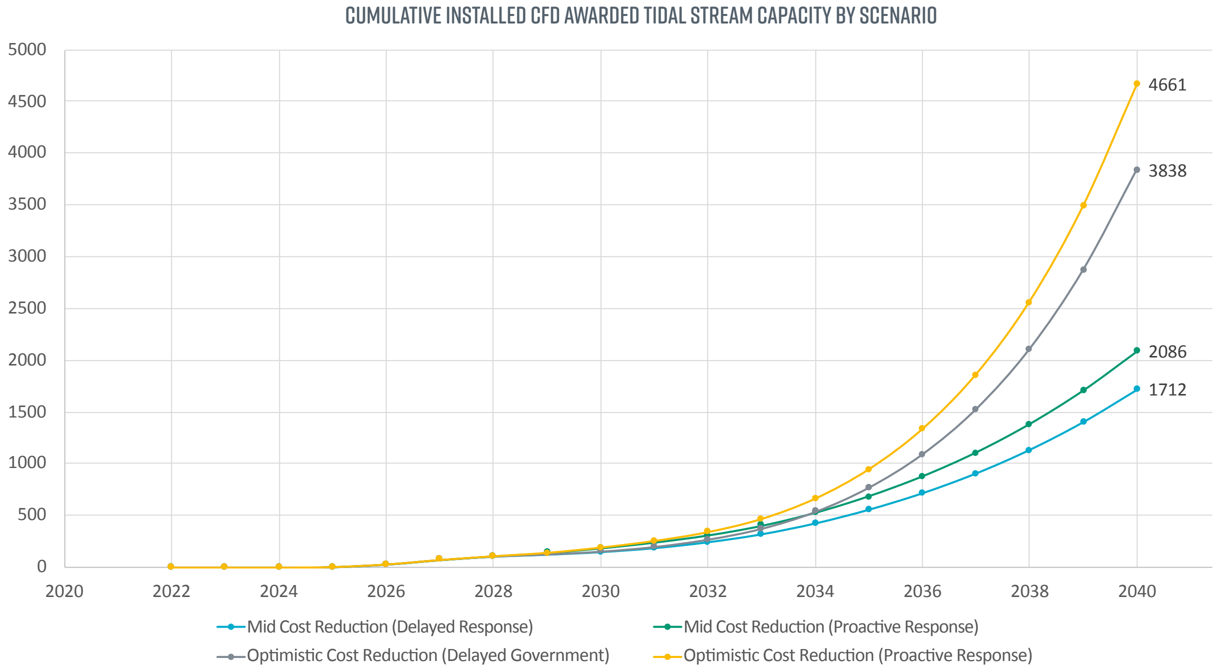

Figure 3: Cumulative CfD awarded tidal stream capacity based on technology impact and government action

Based on the findings in Figure 2 and Figure 3, recommendations have been put forward to support technology innovation alongside supporting policies which maximise its impact. Key recommendations to support technology innovation include:

- The establishment of an industry-wide programme that looks to commercialise and standardise key TS components.
- Continued collaboration between academia (e.g., Supergen ORE Hub), public funding programmes

(e.g., Innovate UK) and research organisations (e.g., ORE Catapult) which support/provide targeted funding for innovation and R&D.

Looking into the formation of required policies, recommendations include:

- A clear government target for TS (e.g., ~1GW by 2035 as per MEC recommendations).
- The establishment of a cost reduction monitoring framework (CRMF) for TS, as was done for fixed bottom offshore wind.
- The introduction of non-price factors in the CfD allocation process which recognises the benefit of TS predictability and its potential to create local content & gross value added (GVA).
- A sector deal for TS similar to that which exists for offshore wind. This can help in achieving a set target for installed TS capacity, aid local content and job creation in coastal communities, as well as maximising the export potential of TS products and services [4].

In the concluding section of this report, further TS technology roadmapping activities which are being considered beyond the scope of this work are also discussed. This includes the roadmapping of innovation areas beyond those covered in this report, which can also play a role in coordinating a CRMF for TS.

1 INTRODUCTION

As of Q1 2024, the TS sector finds itself at a pivotal point, with the first commercial scale array deployments underway. In 2022, a number of UK-based TS projects secured a CfD strike price of £178.54/MWh[1] at AR4 [5], utilising the full £20m/year ringfence for TS projects [6]. In 2023, TS was allocated a reduced ringfence of £10m/year at AR5 [7], with a strike price of £198/MWh being reached and 53MW of capacity being awarded [8]. This is a significant sign of the industry maturing despite an increased strike price at AR5, with two allocation rounds in a row securing a combined ~94MW of TS capacity. This indicates government commitment not seen previously for array scale deployment and the contribution of TS to the UK's energy mix. However, with the majority of AR4 and AR5 projects not expected to be commissioned until 2027/2028, it is crucial that ringfenced support from the UK Government is maintained and increased accordingly beyond AR5. By doing so, this ensures that costs are given greater opportunities to fall and allow TS to reach a LCoE of below £80/MWh by the time 1GW of capacity has been installed globally [9]. Failure to do so will result in fewer projects with an increased delivery cost which will jeopardise the UK's first mover advantage in marine energy, with a reduced ringfence already risking such according to the MEC [10].

Referring back to the 53MW of TS capacity secured at AR5, it should be noted that around two-thirds of this capacity was awarded due to the absence of bids put forward for floating offshore wind (FOW) projects, with FOW sharing the same technology pot (Pot 2) as TS at AR5. For greater context, offshore wind - both floating and fixed bottom received no bids at AR5 due to developers stating that the administrative strike price for both technologies was too low. As such, this would prevent the commercial viability of any projects awarded a CfD under the current market conditions in which inflation has caused a significant rise in project costs[2]. As a result, the £10m/year ringfence in AR5 only secured ~18.1MW of TS. This, alongside an increase in the Allocation Round 6 (AR6) administrative strike price for TS (£202/MWh to £261/MWh) highlights again the need for proportionate ringfenced support in future allocation rounds before non-price factors can fully level the playing field for TS in the long term [11].

According to modelling from the Offshore Renewable Energy (ORE) Catapult's Analysis and Insights team, TS LCoE is expected to fall to £116/MWh by 2030, with around 200MW of capacity operating in the UK by then [3]. While this is a forecasted LCoE approximately three times that of fixed bottom offshore wind during the same period [12], these figures fail to recognise the whole system benefits that TS offers, such as its predictable nature. With this predictability having been modelled, it is expected to contribute towards reductions in the use of gas peaking plants during times of high demand and low wind output, thus contributing to an increased security of supply and a lower carbon intensity in wider energy system operations [2]. This increased security of supply becomes even more desirable as UK power prices reached an all-time high in 2022 [13], and are expected to remain far higher than pre-energy crisis levels in the years to come despite a forecast drop throughout 2023 [14].

Looking forward, the MEC is calling on the government to adopt a target of 1GW of marine energy (Wave & TS) by 2035 [9]. ORE Catapult estimates that approximately 900MW of this could come from TS [3]. For this to come to fruition a combination of reduced technology costs, improved volume manufacturing capability, and maintained government support are paramount.

The amount that TS LCoE can be reduced between now and 2050 will also have implications on the levels of TS that are deemed optimal within the wider energy system. Commissioned by ORE Catapult, Imperial College London's Integrated Whole Energy System modelling suggests that the optimal installed capacity of TS at a 2050 LCoE of £40/MWh is as high as 20GW. Although these are only parameters

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[1] Prices given in all CfD auction rounds are based on 2012 prices.

[2] Offshore wind – both floating and fixed bottom – received no bids at AR5 due to developers stating that the administrative strike price was too low. As such this would prevent the commercial viability of any projects awarded contracts of difference under the current market conditions in which inflation has caused a significant rise in project costs.

taken from one simulation model, the findings conclude that a premium for energy from TS is warranted by allowing lower whole-system costs compared to simply installing additional wind generation [2]. Moreover, research by ORE Supergen and the Policy and Innovation Group at the University of Edinburgh indicates that the installation of 12.6GW of marine energy (6.4GW of wave and 6.2GW of TS) would reduce UK energy system dispatch costs by over £1bn per annum by 2050. Furthermore, the installation of such levels of wave and TS capacity would deliver up to £8.9bn of GVA to the UK economy [14].

In this TS technology roadmap, ten innovation areas of priority are reviewed with regards to their function within the TS energy system. This report also provides coverage on the barriers that stand in the way of the commercial uptake of each innovation, and the final aggregated LCoE reduction potential that each innovation area can provide for the TS sector. The innovations selected for this report are believed to bring about the fastest cost reductions, and by producing a roadmap which focuses on each of their challenges and benefits, a clear strategy for innovation support can be provided which will enable a continuous downward LCoE trajectory. Such a strategy will support the achievement of recommendations set by the MEC, as well as net zero targets set by the UK Government.

1.1 REPORT AIMS

The key aims of this project are as follows:

- Identify the top 10 priority innovations required to further commercialise and drive down TS LCoE.
- Achieve consensus-based innovation cost reduction figures backed by industry.
- Provide stakeholders in government and industry with a clear range of cost reduction pathways.
- Pinpoint where targeted funding for R&D and testing activities enable the fastest cost reductions.
- Assess the limitations of the current CfD allocation structure and how non-price factors are needed to allow greater TS deployment to maximise its subsequent impact on the wider energy system.
- Identify areas for potential collaboration between industry, academia and research organisations to bring about the most impactful research projects and intervention strategies.
- Produce a TS technology innovation roadmap which can be iteratively updated and expanded as the sector continues to evolve in size and maturity. The objective behind this activity is to support the rollout of TS technologies so that ~1GW of cumulative installed capacity in the UK can become feasible by 2035.

1.2 THE TIGER PROJECT

In 2019, the Interreg France (Channel) England Programme approved the biggest ever Interreg project. The TS Energy Industry Energiser project, known as TIGER, was an ambitious €48.4m project, of which €32.05m (66%) came from the European Regional Development Fund via the Interreg France (Channel) England Programme. It was designed to be a game changer for the European TS Energy sector by bringing together leading TS developers to collaborate and share best practice to accelerate deployment and provide evidence of cost reduction.

The project launched in October 2019 and completed in July 2023. The project was led by ORE Catapult and brought together a consortium of 18 organisations including TS technology developers, research centres, project developers and academia. The project delivered new designs for improved performance and lower cost turbines, as well as associated infrastructure and ancillary equipment. It established cross-border partnerships to develop, test and demonstrate new technologies at several locations across the Channel region and used the learning from these developments to make a stronger, more cost-effective case to the UK and French Governments that TS should be a part of the future energy mix. The TIGER project demonstrated that TS is a maturing industry which can achieve an accelerated cost reduction pathway, and positioned the Channel region at the heart of the sector by:

- Addressing technology challenges.
- Building the supply chain.
- Switching on new sites.
- Installing new turbines.

1.3 REPORT STRUCTURE

Section 2 will present a literature review which describes the current state of the TS industry as well as the key issues and challenges that it faces at present.

In Section 3, the methodology used to score each innovation area accordingly is described.

In Section 4, the ten priority innovations of interest within this report are presented. These innovations are those which are predicted to bring about the greatest individual reductions in TS LCoE.

In Section 5 each innovation area is covered in greater detail, with the current status and existing challenges associated with each innovation area being described. The estimated LCoE reduction that each innovation area offers is also provided. Much of the information presented in this section was acquired through industry stakeholder engagement which spanned TS technology developers, supply chain, and academia.

Section 6 covers each innovation area in terms of its TRL, CRL, case for intervention to enable commercialisation, and HSE impact. Regarding the scoring criteria described; much of this is based on the criteria used in the Offshore Wind Innovation Hub (OWIH) Roadmaps, which are managed by ORE Catapult, and track the progress of over 300 pre-commercial innovations that can provide a range of benefits of the offshore wind sector. As such, these roadmaps serve as an industry prioritisation tool within offshore wind. This section also provides a cost trajectory roadmap based on the commercialisation timeline of each innovation area and how this impacts the LCoE of fixed and floating TS devices until 2035. Finally, this section discusses the limitations of the current CfD allocation structure in reaching the required rollout of TS projects that support a strong, continuous cost reduction trajectory.

Section 7 concludes this report with final recommendations made to support ~1GW of TS in the UK by 2035. Reference is also made to planned future roadmapping activities which centre around TS technology innovation and further cost reduction.

2 LITERATURE REVIEW – CURRENT STATE OF THE SECTOR

In this section, a review of existing literature is presented to give a detailed overview of the current state of the TS sector. In Section 2.1 the wide range of existing TS device designs are presented alongside the pros and cons that each of these designs exhibit. In Section 2.2, the main cost reduction enablers that have allowed TS to go from a LCoE of around £500/MWh at 1MW of cumulative deployment [16], to a CfD strike price of £178.54/MWh at AR4 are described. Moreover, several of these same enablers are what will allow TS to go to below £80/MWh at 1GW cumulative deployment [9]. With this report being centred around technology innovations that will support continued TS cost reductions; mention is also given to non-technical barriers that slow the downward cost trajectory of TS in Section 2.3.

2.1 TIDAL STREAM TECHNOLOGY TYPES

With TS being at an earlier stage of development, the industry is yet to see the same design convergence seen in more mature sectors (e.g., the wind industry converging on three bladed horizontal-axis turbines). At present, TS devices can mostly be broken down into two main types: fixed and floating, as can be seen in Table 2 [3]. However, within these two device configurations comes a wide range of differing designs comprising of horizontal and vertical axis turbines. Beyond these, there are alternative designs such as fixed “kite” designs and floating kinetic keel designs. Section 2.1.1 covers horizontal axis devices which are the most numerous TS device deployments to date. Section 2.1.2 covers the successful deployments of vertical axis devices while Section 2.1.3 presents the range of alternative solutions which fall outside of the orthodoxy of horizontal and vertical axis designs.

	Microscale <100KW	Small scale 100KW - 1MW	Utility scale >1MW
Fixed foundation Horizontal axis turbine	**Guinard Energies Nouvelles (FRA)** P66, P154 **ORPC (USA)** RivGen	**Nova Innovation (GBR)** M100, 200KW turbine **QED Naval (GBR)** Subhub Community Design **Sabella (FRA)** D08, D10, D12 **Proteus (GBR)** AR500 **Verdant Power (USA)** TriFrame Gen5 **Hydrowing (GBR)** HW500, HW1000	**Andritz Hydro Hammerfest (AUT)** Mk1 1.5MW turbine **Proteus (GBR)** AR1500, AR2000, AR3000 **Hydrowing (GBR)** HW1500
Fixed foundation Vertical axis turbine	**Instream Energy Systems (CAN)** 25KW hydrokinetic turbine system		**Hydroquest (FRA)** Oceanquest 1, Oceanquest 2
Fixed foundation Other	**Minesto (SWE)** Dragon 4	**Minesto (SWE)** DG100, DG500 **Seaqurrent (NLD)** TidalKite	**Minesto (SWE)** Dragon 12

	Microscale <100KW	Small scale 100KW - 1MW	Utility scale >1MW
Floating foundation Horizontal axis turbine		**Orbital Marine Power (GBR)** SR250 (ScotRenewables) **Sustainable Marine Energy (GBR)** PLAT-I 4.63, PLAT-I 6.40 **Aquantis (USA)** Tidal power tug	**Magallanes (ESP)** ATIR **Orbital Marine Power (GBR)** O2, SR2000 (ScotRenewables)
Floating foundation Vertical axis turbine	**Gkinetic (IRL)** CEFA12	**Aschelous Energy Ltd (GBR)** FITS Platform	
Floating foundation Other		**BigMoon Power (USA)** Kinetic Keel (prototype) Kinetic Keel (~0.5MW)	

Table 2: Current and future tidal stream devices by configuration and scale (entries in black text represent devices that have seen real world deployment, while devices in blue text are those currently in development) [3]

2.1.1 FIXED AND FLOATING HORIZONTAL AXIS DEVICES

When comparing fixed and floating TS devices, both have their advantages. For example, fixed devices are hidden from the sight of the nearby public, which can help in the consenting process due to having a negligible visual impact. With adequate environmental planning and the use of foundations with reduced spatial requirements, the impact that fixed devices have on the local marine environment can be minimised. However, due to these devices being placed underwater, their retrieval becomes more difficult and therefore results in increased O&M costs in the case of any unplanned maintenance requirements [17]. Additionally, because of the proximity of fixed devices to the seabed they are limited to a narrower range of site conditions which, in several cases, can limit their access to highly energetic site locations [18]. Instances which can limit the use of fixed devices in certain site areas include challenging bathymetry and high turbulence.

For floating devices, their placement at the water's surface brings about considerable O&M advantages as there is no need for complex underwater operations which are subject to weather windows as well as tidal flow conditions [17]. The installation of floating devices can also be less complex as mooring and anchoring systems can be quickly deployed during slack tides, thus reducing or even eliminating reliance on dynamic positioning vessels [19]. Albeit mooring systems and floating devices can be more difficult to engineer compared to fixed foundations [18]. Furthermore, floating devices are also far more susceptible to wave loading due them sitting at the top of the water column where induced wave forces are at their highest. Such wave loading can also have a bearing on the quality of power delivery and the longevity of floating devices in general [20].

When comparing the LCoE of fixed and floating TS devices, the differing device scales, nuances in designs, and stages of development that each is at brings about variation in final LCoE calculations. However, projects which secured a CfD at AR4 will need to reduce project costs to below £178.54/MWh by around 2027 to be commercially viable. This is a considerable cost reduction requirement considering that as of 2018, the weighted LCoE of TS was around £300/MWh [16]. Such cost reduction appears realistic for certain devices such as OMP's O2 device which targeted a LCoE of under £200/MWh for its first device deployment [20], which was installed at the European Marine Energy Centre's

(EMEC) test facilities, with the device exporting power to the grid as of July 2021 [21]. However, final LCoE estimates for devices installed at EMEC, Meygen and Morlais will not be representative of devices installed at commercial TS sites, as the consenting and infrastructure are already accounted for, which removes a considerable portion of the costs associated with getting a device or array up and running.

2.1.2 NOTABLE VERTICAL AXIS DEVICES

Although most TS devices to be tested at scale have been horizontal axis devices, some promise has also been shown in vertical axis devices. The most notable of these is Hydroquest's Oceanquest 1 which was successfully installed and connected at EDF's Paimpol-Bréhat tidal testing site in Brittany in July 2019. After two and a half years of successful operation, the device was successfully retrieved in October 2021 [22]. Beyond this, HydroQuest are in the development phase of a 17.5MW project at La Raz Blanchard where they intend to use one of their next generation devices (most likely the Oceanquest 2).

2.1.3 ALTERNATIVE DEVICE DESIGNS

Outside of fixed and floating designs are a wide range of alternative designs. These include design concepts such as oscillating hydrofoils, venturi turbines, Archimedes screws, and kinetic keels. Such designs, however, are at very early stages of development, with the possibility that commercialisation is never reached for some. Of all the alternative designs, Minesto's "kite" design has shown the most merit to date. The device resembles an underwater kite, equipped with a small rotor, which generates electricity as it "flies" through the water column. The operating principle is similar to airborne wind technology. The main advantage of this technology is its ability to provide generation in low flow areas, as the relative speed of the device moving through the water column can have an additive effect to the incident flow speed which effectively increases the flow speed exerted on the rotor. This ability to perform in low flow sites brings about a niche in Minesto's device as it can utilise sites that other TS devices would not be capable of, by virtue of being designed to operate in locations with the highest flow speeds. However, the device is more complex in nature than more conventional fixed and floating designs [23]. In terms of Minesto's device deployments, the most notable are those which took part In Vestmannasund in the Faroe Islands which saw initial delivery of electricity generation to the grid from two of their DG100 devices in December 2020 [23], [24]. More recently, Minesto doubled production capacity at Vestmannasund by installing two of their 100KW Dragon 4, with the first being installed in May 2022 [25], and the second in December 2022 [26].

2.2 COST REDUCTION ENABLERS

Throughout the industry it is agreed that continuous cost reduction can be achieved through a number of means so that the LCoE of TS becomes competitive with other, more established forms of renewable generation. For example, ORE Catapult's report Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit from 2018 presents the view that cost reduction in the near-term will be enabled through a combination of initial accelerated reductions (increases in site and device capacity, accelerated learning, and increased economies of volume), learning by doing and innovation, and reductions in the cost of capital [16].

Thus far, initial accelerated reductions have taken place via economies of scale through increases in turbine capacity (e.g., Orbital Marine Power (OMP) scaling up from the 250KW SR250 turbine to the 2MW SR2000 and O2 turbines) [27]. Reductions via accelerated learning (cost reduction as witnessed per each doubling of capacity) has also taken place, with conservative learning rates for TS being estimated at 7% [28]. Examples of accelerated learning can be found in the approaches taken by developers such as Nova Innovation who have yet to scale up from the use of 100KW devices, but have seen their Shetland Tidal Array go from 3 devices in 2016, to 4 devices in 2020, to 6 devices in 2023, with turbines 5 and 6 offering reduced TS costs via increased device reliability and reduced cable requirements, through the use of a subsea hub which connects the two turbines to a single export cable [29]. However, despite some progress in improving the manufacturability of key TS system components, many barriers still remain in achieving the manufacturing volume required to achieve the cost reductions required to support the development of commercial scale arrays by the end of the 2020s, with the most critical barriers to volume manufacturing being inconsistent or lacking access to revenue support schemes, and long lead times in component manufacture and procurement processes, which are highly likely to cause serious bottlenecks if not properly addressed in the coming years [30].

Learning by doing and innovation has yielded both cost reduction and increased reliability across the last decade, but more of the same will be required across the next decade to ensure cost reductions support the commissioning of TS projects in the hundreds of megawatts by the 2030s. For example, between 2003 and 2020 the most common failure cause on TS systems was blade failure, with much of this being down to the underestimation of mechanical loads during the design phase [31]. As a result, more caution has been taken in blade designs which has significantly improved their reliability. However, this has led to instances where blades may be over-engineered which results in more expensive designs being used. Furthermore, with the wide variations in blade designs and their structural complexities, the lack of standardisation in this area is a factor which can keep the price of blades relatively high as larger rotor diameters of up to 28m become commonplace in the advent of 3MW+ devices being put in the water. The standardisation of blades via publicly funded initiatives and the use of advanced blade materials are two examples of learning by doing and innovation that will support further cost reductions as blades continue to scale up [29].

For longer-term cost reductions in the TS sector, Ref [16] asserts that this will be achieved by further learning by doing and innovation (much of which will be covered in the later sections of this report), and further reductions in the cost of capital. The impact of both near and long-term cost enablers are shown in Figure 4.

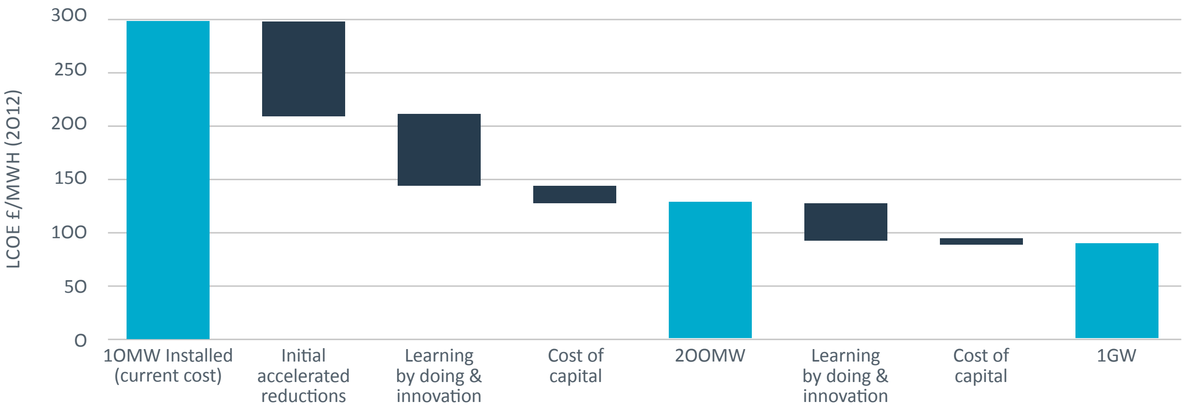


Figure 4: Tidal stream LCoE, near and long-term cost reduction enablers [16]

2.3 NON-TECHNICAL BARRIERS TO TIDAL STREAM GROWTH

Although this report is focused on cost reduction through technology innovation, mention must be given to non-technical barriers that slow the downward push in TS LCoE. These non-technical barriers are the weighted average cost of capital (WACC) (Section 2.3.1), high insurance premiums which provide inadequate coverage (Section 2.3.2), the lack of warranties available for TS devices and their components (Section 2.3.3). and issues in the consenting process (Section 2.3.4).

2.3.1 WEIGHTED AVERAGE COST OF CAPITAL

Referring to Figure 4, as far as reductions in the cost of capital are concerned, the larger projects become, the easier it will be for developers to obtain lower interest rate financing via commercial debt. This serves as a progression from what was typically done in the past where TS projects were financed via equity. A major factor in financial institutions providing lowered interest rates is through increasing the bankability of TS, brought about through technology de-risking and stabilised revenue through mechanisms such as CfD.

With regards to technology de-risking, TS deployments at this stage have largely used highly bespoke components with long manufacturing lead times and have been burdened by lack of suitable vessels for installation and operations and maintenance (O&M). Because of this, it has been far harder to determine reductions in revenue from prolonged turbine downtime in TS projects due to their early-stage nature. This uncertainty makes it difficult for lenders to determine risk and as a result makes it far harder for developers to access commercial debt at lower interest rates that will increase their project's internal rate of return (IRR). This is due to the perception held by lenders that project developers will fail to service such debt, and as creditors, would subsequently risk taking over what could become a defunct asset stranded at sea [32]. By reducing the WACC from 8% to 6.4%, the LCoE of TS can be reduced by 9.6% [33], with other estimates indicating that each 1% reduction in WACC can reduce TS LCoE by 7% [34].

2.3.2 HIGH INSURANCE PREMIUMS AND INADEQUATE RANGES OF COVER

Insurance premiums for TS projects remain prohibitive and therefore have a noticeable contribution towards final project LCoE. This issue is exacerbated at present due to the insurance market being in a "hard" phase which is even causing issues for developers of more mature renewable technologies such as solar PV and offshore wind. Moreover, such developers are concerned that pathways to net zero are being hindered by current insurance market conditions. As is expected, the impact of these insurance market conditions is felt even more greatly by less established forms of generation such as TS. Another factor at play which increases insurance premiums for TS developers is the lack of performance data that insurers have available to determine appropriate premiums for a given level of cover. This creates a dynamic where appropriate cover cannot be provided without sufficient operating hours from TS projects, but developers are unable to take the risk of procuring technology to support increased operating hours as no appropriate insurance is made available [32].

To overcome insurance market failures a study was carried out as part of the TIGER project (the Ocean Energy Accelerator) which developed a protected cell company (PCC) captive insurer structure to provide robust insurance products which are adequate in enabling new marine energy projects to be tested, demonstrated, and deployed at commercial scale [33]. For greater context, PCCs consist of a core cell set up by the government and several protected accounts (or "cells") that tap into the core cell. Although each PCC is a single legal entity, each cell benefits from legal separation of assets and liabilities from the other cells within the PCC. This allows various insured parties to transfer risk to the same captive, with each having differing premiums and exposure levels [35].

2.3.3 A LACK OF WARRANTIES FROM ORIGINAL EQUIPMENT MANUFACTURERS

Due to the nascent nature of the TS industry, TS developers and original equipment manufacturers (OEM) will have far weaker balance sheets compared to their counterparts in more established industries such as offshore wind. This results in warranties which are very limited in scope and are therefore not deemed bankable by financers. Warranties that are offered very rarely go beyond coverage of parts and labour. There is a strong desire for clients of TS equipment manufacturers to provide performance and availability guarantees in their warranties which would make their scope of coverage more akin to that of offshore wind. This would result in warranties being tied to the provision of long-term O&M contracts which is far beyond what most OEMs can afford to offer at present.

To help partially resolve the issue of warranties which are limited in scope, one solution could be to create an alternative to commercial warranties for the first three to five years of a TS project's operation. This alternative solution should cover O&M, an element of revenue shortfall following technical failures, and coverage of the entire TS system, instead of individual components. After the first few years of a project's operation, a long-term mutual insurance structure can be implemented which provides something similar to an O&M contract seen in more mature renewable energy industries [31].

2.3.4 ISSUES IN CONSENTING

Complexities in the consenting process are another area which slow the rate at which an extensive TS project pipeline can be developed. In previous years the planning and approval process has been notably difficult, with assessments often being expensive and highly technically challenging in comparison to the scale of projects being developed, as well as the level of environmental risk involved [16]. All this cost is borne by developer shareholders at their own risk. Agreement remains to be reached with regulators on what steps should be taken to streamline the consenting process while ensuring adequate environmental impact mitigation strategies are adopted by developers. This is a challenge faced by other offshore renewable energy industries including floating and fixed bottom offshore wind and not TS in isolation.

These are issues which will be largely resolved via learning by doing as a greater TS project pipeline comes into being as the 2020s progress. While improvements in the regulatory landscape serve as the main driver to resolve this barrier, technology innovation can also play a role. Technologies of assistance in this area include mobile integrated solution devices, high frequency tagging systems for fish and birds, and advanced data processing tools.

3 METHODOLOGY

Before each innovation area can be covered in full throughout Sections 4 and Section 5, the methodology used to obtain final LCoE reduction figures must first be described. As well as final LCoE reduction figures, TRL, CRL, case for intervention, and HSE impact of each innovation area are also presented as part of a technology cost reduction roadmap illustrated in Section 6 (See Appendices A-D for further details).

Before stakeholder engagement was initiated there were already initial cost reduction figures available through previous TIGER work packages, with T3.2.2 Tidal Stream Site Cost Reduction Report being of the most use as it covers many of the same innovation areas discussed in this report [33]. In addition to this, numerous LCoE reduction estimates were obtainable from individual developers via previous TIGER stakeholder engagement which focused on technologies that feature as part of their wider TS systems. Using the two aforementioned resources, initial LCoE reduction ranges could be formulated for each innovation area.

To validate these initial LCoE reduction ranges they were put forward to the range of developers we engaged with, as well as other stakeholders where this was felt as being necessary. Where developers were unable to provide LCoE reduction figures for either purposes of confidentiality or because they lacked available, reliable data; LCoE modelling was conducted which calculated the impact that each innovation area had against a base case TS array. The key details of this TS array are listed below:

- 8MW capacity in total.
- Comprised of 4 x 2MW turbines.
- 4 separate export cable connection points.
- A baseline LCoE of £305.40/MWh.
- A discount rate of 8%.
- A 25 year project lifetime.

When looking at the scoring methodology used for gauging the TRL, CRL, case for intervention, and HSE impact of each innovation area, greater detail can be found in Appendices A-D. Much of the scoring criteria used here is largely based on what is used in the OWIH Hub Roadmaps. For the purposes of this report each score is defined as either being low, medium, or high. For scoring TRL and CRL, low, medium, and high represent TRL and CRL 1-3, 4-6, and 7-9 respectively.

Regarding the technology cost reduction roadmap in Section 6, the time at which each innovation area has an impact is based on its anticipated commercialisation date. In the context of this report, the commercialisation date of each innovation area coincides with the year that projects from each respective allocation round (e.g., AR4, AR5, etc) are expected to be commissioned. For example, if an innovation area is expected to initially feature on AR4 projects, then the forecast commercialisation date will be 2027.

For calculating the cost reduction trajectory experienced by the time TS projects from each allocation round are commissioned, the roadmap in Section 6 follows three scenarios: a conservative, an optimistic, and a mid-range cost reduction trajectory. In the conservative scenario, the minimum expected LCoE reduction potential is applied to all innovation areas commercialised within a given year, whereas in the optimistic scenario, the maximum LCoE reduction potential is applied. For the mid-range scenario, the LCoE reduction potential applied is the sum of the maximum LCoE reduction potential subtracted by the the minimum LCoE reduction potential. For example, if an innovation area has a LCoE reduction potential between 5-10% then a 7.5% LCoE reduction will be applied in this instance.

Within this roadmap the latest innovation area of interest to be commercialised will feature on AR7 projects that are estimated to be commissioned by 2030/2031. However, cost reduction trajectories are forecast to 2035 where it is anticipated at this stage that close to 1GW of TS is installed in the UK, as per the target recommended by the MEC. Beyond 2030, it is assumed that continued cost reduction is driven by a combination of:

- The non-technical barriers mentioned in Section 2.3 being largely resolved.
- The full beneficial effects of volume manufacturing taking hold.
- The further optimisation and evolution of innovation areas covered in this report.
- The introduction of new innovations not mentioned in this report.

4 LIST OF INNOVATIONS

In this section, ten innovation areas of focus are presented which will be the central focus for the remainder of this report. These innovations have been selected due to each scoring highly in their LCoE reduction potential during previous work carried out by ORE Catapult as part of the TIGER project, with this report building on many of the findings presented in “T3.2.2 Tidal Stream Site Cost Reduction Report” [33]. Below are the ten innovation areas to be covered in greater detail in sections 4 and 5, presented with a short description of the purpose they serve within the wider TS system.

1. Step Change in Rotor Diameters – By increasing rotor diameters, a greater area of tidal flow can be captured, and from this, higher yields can be achieved on a turbine of a given capacity.
2. Subsea Hubs – These enable multiple TS turbines to be connected to a single export cable. In doing so, cabling requirements for TS projects can be massively reduced, all of which becomes of critical importance once TS arrays reach commercial scale.
3. Array Optimisation to Minimise LCoE – By optimising the spatial arrangements of turbines in a given array, yield and turbine loading can be minimised resulting in lower LCoE across a TS project’s lifetime.
4. Innovative Anchors for Floating Devices – By transitioning from gravity based to rock bolt anchoring solutions, significant reductions can be made in material usage, environmental footprints, and the time taken to install floating TS devices.
5. Step Change in Rated Generator Power – By increasing the rated power of the turbines used in each array, less turbines can be installed for a site of a given capacity. With less turbines required, less cabling and supporting infrastructure is needed, all of which play a role in reducing O&M requirements across a TS project’s lifetime.
6. Controllers that Optimise Lifetime Turbine Performance – Control strategy algorithms allow turbines to generate higher yield across the range of flow speeds they encounter as well as minimise turbine loading. This increases revenue and lowers O&M requirements across a project’s lifetime.
7. Optimised Foundations for Fixed Devices – By transitioning from gravity based to piled foundations, significant reductions can be achieved in the material usage and environmental footprints of fixed TS turbine foundations.
8. Optimising and Standardising Wet Mate Connectors – Wet mate connectors enable faster and cheaper installation and retrieval of TS devices. However, many wet mate solutions for the TS industry remain either highly bespoke or sub-optimal for the devices they are being connected to.
9. Condition Monitoring of Cables – Having effective condition monitoring allows potential faults and failures to be detected earlier and plays a key role in minimising turbine downtime.
10. Optimised Individual Pitch Control – Enhanced control of individual blade pitch angles enable greater yield and load management to be achieved across the full range of flow speeds that a TS turbine encounters.

5 STAKEHOLDER ENGAGEMENT

This section covers the report's innovation areas of focus in the greatest amount of detail. For each innovation area, a general background description is given which presents information on where each innovation area stands at present and the role it must play in improving and reducing the LCoE of future TS systems. After this, the innovation challenges that need to be overcome to bring each technology to commercialisation are discussed. As mentioned before, the stakeholder engagement undertaken was achieved by reaching out to a combination of TS technology developers, supply chain, and academia.

5.1 STEP CHANGE IN ROTOR DIAMETERS

5.1.1 BACKGROUND

By enabling larger rotor diameters (longer blades), a greater area of tidal flow can be captured, and from this, a greater amount of kinetic energy can be harnessed. With larger rotor diameters offering higher AEP, significant LCoE reductions are possible as a result. For example, increasing rotor diameters from 18m to 24m on the devices used at Meygen phase 1A would improve energy yield per turbine by 34% [36].

5.1.2 INNOVATION CHALLENGES AND LCOE REDUCTION POTENTIAL

Effort must be taken to determine at which sites larger rotor diameters can be used. This will present challenges for sites which use fixed bottom devices due to their proximity to the seabed which will limit the length of blades that can be used in several instances, while floating devices will have to contend with sea surface limitations. For both fixed and floating devices, the cost of manufacturing, transporting and installing larger blades, as well as any device design changes that need to be made to accommodate greater mechanical loads must be weighed against site-specific increases in AEP. To improve confidence in load calculations and to prevent over-engineering in larger rotors, the use of advanced design software tools will play a leading role in supporting cost-optimal rotor sizes beyond what is available today.

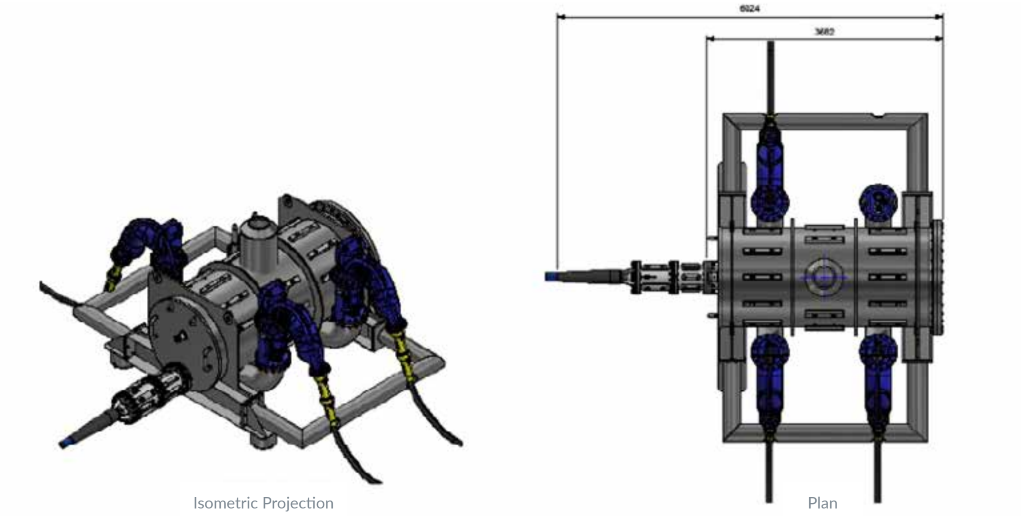
At this stage, multiple developers have highly optimistic estimates of the LCoE reductions that can be achieved by utilising larger rotor diameters, with these sitting at around 20% (and higher in certain instances). Such high cost reduction estimates can be seen as achievable for TS, with increased rotor diameters serving as one of the most effective LCoE reduction strategies in the early days offshore wind. However, it should be emphasised again that TS rotor diameters will be limited by seabed (fixed devices) and sea surface (floating devices) clearance requirements, unlike offshore wind which faces far less spatial constraints in terms of the rotor diameters that can be used.

5.2 SUBSEA HUBS

5.2.1 BACKGROUND

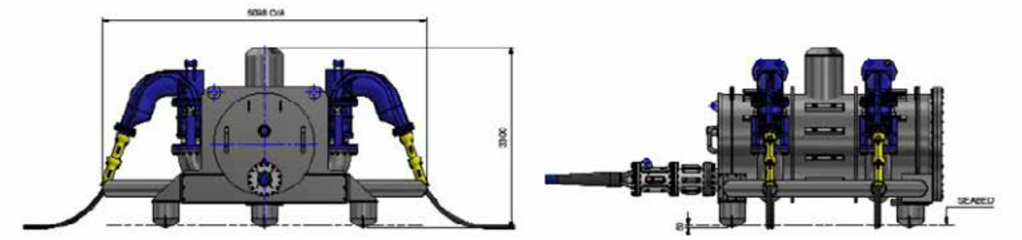
Subsea hubs enable multiple TS turbines to be connected to a single export cable. Having the ability to group 4-10 turbines to a single export cable is critical in reducing TS LCoE, with subsea hubs providing estimated capital expenditure (CAPEX) savings of 80% on cabling and associated infrastructure costs [19]. At present, most subsea hubs take the form of a submersible junction box. Thus far, the Meygen

Phase 1a project has implemented a subsea hub which connects 4 TS turbines to a single export cable, with their first subsea hub installed in September 2020. This subsea hub solution is displayed in Figure 5 [37]. More recently, Nova Innovation used a subsea hub which connected their fifth and sixth turbines at the Shetland Tidal Array in January 2023 [29].



Isometric Projection

Plan



Elevation (Export)

Elevation on Subsea Hub Phase 1 – GA D30301

Figure 5: SIMEC Atlantis subsea hub [37]

In addition to a junction box the subsea hub used by Meygen also features wet mate connectors for the connection of individual turbines, a dry mate connector designed for the connection of an export cable, and an extra wet mate for the connection of an instrumentation sled. To build on this initial design Proteus Marine Renewables – of whom acquired all of SIMEC Atlantis' technology IP as well as its shares in Normandie Hydroliennes, the project developer of a 12MW project in the Raz Blanchard [38] – intend to develop and install a subsea hub which contains internal converters and transformers in future TS array projects. This will maximise the transmission efficiency of TS generation to the onshore grid.

5.2.2 INNOVATION CHALLENGES AND LCOE REDUCTION POTENTIAL

At present, there is a wide range of junction boxes that are submersible by design. However, junction boxes used for TSE applications currently stand at an early stage of development. When considering the required characteristics of subsea junction boxes used for TS, durability is key in ensuring the junction box can withstand the high flow water movement found at TS sites. Greater clarification is also needed on the benefits that subsea hubs would provide for floating TS arrays. Compared to fixed bottom arrays, the level of cost reduction potential for floating arrays will likely be lower because power electronics can be fitted within each floating device's hull, meaning only a submersible junction box would be required to reduce project cabling requirements.

Regarding the future iteration of subsea hub that Proteus Marine Renewables plan to develop; the additional extra weight of internal converters and transformers must be considered in the wider design. On top of this, ensuring both these components are integrated in a manner which minimises the possibility of faults or failures in subsea hub retrieval is crucial in avoiding substantial maintenance costs alongside significant lost generation.

Other than Proteus Marine Renewables, other developers have used (Nova Innovation) or have considered the use of subsea hubs (Hydroquest), with these designs being more akin to a subsea junction box. With different designs being used between different developers, estimates on total LCoE reduction have been subject to variation, with these landing in the region of 10-20%. However, there is the potential for LCoE reductions of above 20%, but this would require the use of subsea hubs in much larger arrays located at distances further from shore.

5.3 ARRAY OPTIMISATION TO MINIMISE LCOE

5.3.1 BACKGROUND

Array optimisation placement strategies can take multiple forms. LCoE minimisation via array optimisation will be achieved through placement strategies which support high yield, greater management of blockage effects, minimised cabling requirements, and reduced O&M through improved load prediction and efficiency in marine operations. High-fidelity modelling serves as one of the best tools available to calculate optimal array layouts at a given site.

At present, multiple models exist which can be used to calculate energy yield from arrays which employ both uniform and non-uniform spacing between turbines, with greater yields being possible when changing the locations of specific turbines. Such modelling indicates that increases in yield of up to 30% can be achieved [36]. However, focusing only on the changing of turbine locations negates many other factors that are at play when seeking to minimise LCoE via array optimisation, with the biggest factor being the highly site specific nature of TS.

Regarding the accuracy of models currently used to gauge array performance, one area which negatively impacts their accuracy is the lack of in-field data to validate against. According to one academic, the availability of data to validate against is made more difficult by developers being unwilling to share such data out of fear of commercial risk, with much of this data having been expensive to gather in the first place. Furthermore, many high-fidelity models used at present only focus on one operating condition at a single site due to the computationally taxing nature of modelling multiple environmental conditions (e.g., bathymetry and wave activity). Improvements in the modelling of turbine loading is also an area which would enable better performance forecasting for TS projects.

Some modelling techniques have been transferred from the wind sector where there are some parallels in wake physics and turbine parameterisation. However, these alone are insufficient to establish confidence in energy yield predictions for the complex conditions and turbine design parameter ranges involved in the optimisation of TS turbines.

5.3.2 INNOVATION CHALLENGES AND COST REDUCTION POTENTIAL

Perhaps the most notable project which investigated LCoE reduction through array optimisation is the EnFAIT project. During EnFAIT, Nova Innovation monitored and collected operational data from turbines at the Shetland Tidal Array. This data was then used to support improved array performance once Nova Innovation's site had been expanded to four, and then six turbines, with different array layouts being tested during the project so that improved array performance could be demonstrated. It should be emphasised that such findings were obtained through a multi-year EU funded research project, and for most commercial developers who do not have the same level of support to test multiple array layouts before project commissioning, computer-based modelling will likely serve as the primary means of optimising their array layouts. Figure 6 displays the array design approach used during the EnFAIT project. This array design approach was built by combining a site resource model, a computational fluid dynamic based wake model. And a blade element momentum model [39].

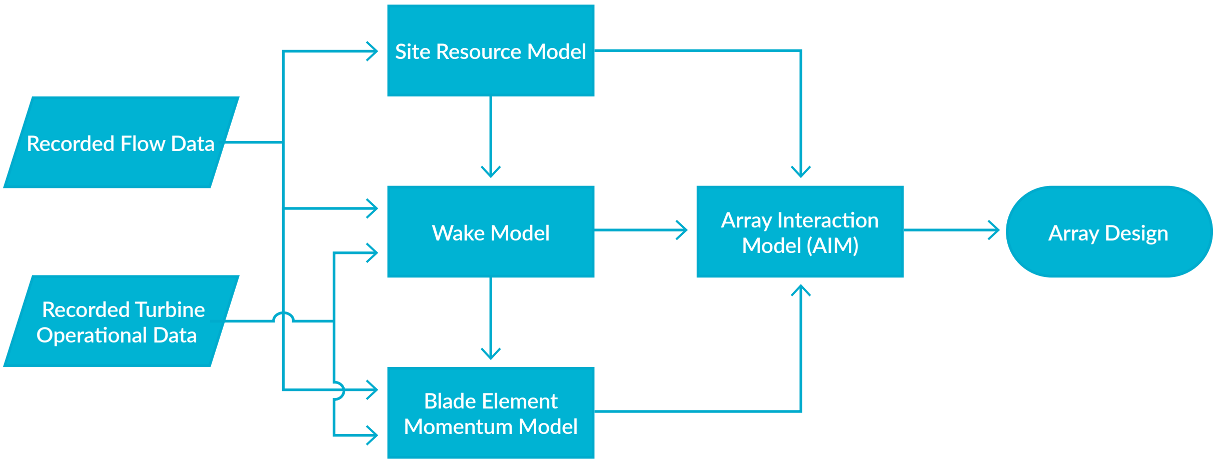


Figure 6: Modelling approach flow design [39]

For models to be improved they must be capable of predicting flow speed through a range of turbine diameters at differing water depths, and the impact that wave activity will have on these parameters. This must be done in a manner that is affordable and efficient by not being too computationally taxing as previously mentioned. One factor that is impeding the development of improved models according to an academic respondent is that many developers only consider site areas with the highest tidal flow when looking to place their turbines. Part of this reason could be that tidal developers with their relatively weak balance sheets need to demonstrate the potential of their technology and target yield maximisation as the central means to improve investor confidence in future projects. In addition to this, it was stated during stakeholder engagement that, overall, there is an underappreciation of array modelling from developers.

In terms of enabling actions to support the development of next generation array modelling, collaboration between developers and academia should be sought. It would enable greater transparency from developers to share data which will be required to improve bespoke models, thus partially combatting the site-specific nature of TS modelling which impedes LCoE reduction via optimised placement strategies. It is also expected that improvement in models will play a role in enhancing investor confidence by providing greater clarity between the P50 and P90 yields of various sites.

In terms of final LCoE reduction, a reduction in the region of 10-20% was calculated. However, as of March 2022, the EnFAIT project stated that they have achieved a 40% reduction in the cost of TS energy [40], but this was achieved through the testing of different array layouts and not through high-fidelity modelling alone.

5.4 INNOVATIVE ANCHORS FOR FLOATING DEVICES

5.4.1 BACKGROUND

Innovative anchoring solutions can take many forms. These solutions offer lower CAPEX, lower material usage, quicker installation time and lower OPEX throughout the lifetime of a floating TS project in comparison to gravity based and grouted anchors.

One example of an innovative anchoring solution is the use of self-drilling, grout free rock bolt anchors, that which is offered by Swift Anchors and shown in Figure 7. In addition to their use in the TS sector, Swift Anchor's solution has also been explored for operation in various other sectors including floating wind, floating solar and aquaculture [41], but demonstrations at scale will be required to prove their solutions are appropriate for use in each respective industry. Despite multiple innovative anchoring solutions being currently available for both the TS and FOW sectors, the focus here will primarily be on rock bolt anchor solutions due to the hard nature of seabed seen at most TS sites, with comparison being made to gravity based and grouted anchors.

Figure 7: Swift Anchor's rock bolt anchor (credit: Swift Anchors)

Significant CAPEX costs could be avoided through the use of rock bolt anchors from the huge reduction in material required to support a given mooring load. For example, a one tonne grout free anchor can support a mooring load of around 200 tonnes while having far smaller mass and spatial requirements (i.e., a rock bolt anchor is typically several metres long which is mostly embedded within the rocky seabed, compared to a gravity based solution which requires many tonnes of ballast material while taking up tens of square meters in seabed area). These smaller spatial requirements bring about less environmental impact which can also play a role in streamlining the consenting process. Environmental impact is also reduced compared to grouted connections as these anchors are removable at the end of their life and leave no footprint after a TS project has been decommissioned.

Focusing again on anchor material and spatial requirements; calculating the interface friction between the clump and the seabed is hard to accurately predict on TS systems using gravity based anchors, with the implications of high flow introducing additional hydrodynamic loads which must be considered. This can therefore bring a degree of uncertainty, with there being many cases where additional material is used beyond the actual loading and hydrodynamic requirements, thus worsening the already excessive material usage in comparison to rock bolt anchors.

When considering mooring load management provided by grout free anchors, they have their pros and cons compared to grouted solutions. For example, with grouted solutions, inconsistencies can be experienced during the grout curing process which results in some grouted installations having lower than anticipated load capacities, compared with the same anchors which have cured fully during the installation process. On the other hand, despite grout free anchors being free of the uncertainty that is brought about by the curing process, like a grouted solution, they are also dependent on the strength of the rock in which they are installed, which can be difficult to ascertain across all anchor locations.

Sizable cost reductions may be achievable during the installation phase by using rock bolt anchors instead of gravity based ones, but this is yet to be demonstrated. Much of this would be down to the far quicker installation times and lower vessel charter costs. According to Swift Anchors, their solution can be installed in around 35 minutes over the course of a slack tide period. This gives them the opportunity to install several anchors a day off relatively small vessels, compared to the installation of gravity based foundations which require far larger, more expensive vessels. There have been cases where the cost of vessel hire for rock bolt anchors has been around a quarter that of gravity based solutions.

5.4.2 INNOVATION CHALLENGES AND LCOE REDUCTION POTENTIAL

At present there are a range of rock bolt anchors, both grounded and grout free, that could potentially offer a viable alternative to gravity based solutions, but these are yet to be demonstrated at full scale. Even once a rock bolt anchor has been proven at scale, the lack of standards for rock bolt anchors will remain an issue that requires resolution. A standardised set of anchor sizes which can satisfy a range of device scales across different seabed conditions will need to be agreed upon by the wider TS industry. According to Swift Anchors, this is an area which would enable the biggest cost reduction for their business through the ability to volume manufacture and reduce material usage in the production process. Swift Anchors estimated that such standardisation could reduce their manufacturing costs by 20-30%.

The way in which anchor standardisation is reached is hard to determine at this stage. Regardless, developers have an instrumental role to play in the cost reduction journey by engaging with their suppliers early in the project development phase. By working closely with anchor suppliers to determine aspects such as mooring loads and geometry in the design phase of the wider anchoring/mooring system; costs can be minimised by avoiding excess chain being purchased while maximising the mechanical performance of the system.

In terms of the final LCoE reductions that can be achieved through innovative anchoring solutions, it must be acknowledged that there will be a degree of variation from site to site. This will be influenced by factors such as the bathymetry and geology of the seabed (e.g., sandstone, granite), as well as overburden and the overall strength of the seabed in which anchors are being placed. For example, the strength of the seabed will influence the length of anchor used which will determine overall anchor CAPEX, with weaker seabed requiring longer anchors. However, through previous stakeholder engagement via the TIGER project and internal ORE Catapult modelling, an estimated LCoE reduction of 5-10% can be achieved by using innovative anchoring solutions. To maximise LCoE reductions even further in the future; anchoring/mooring systems should be optimised in shared configurations so that their enhanced efficiency and ease of installation allows for significant decreases in anchor CAPEX across a given project's lifetime. However, shared anchors will only achieve substantial cost reductions once larger floating arrays are developed, whereby they become the cost-optimal solution.

5.5 STEP CHANGE IN RATED GENERATOR POWER

5.5.1 BACKGROUND

Increasing the rated power within a given rotor diameter will increase the amount of energy that is produced at a particular rated flow speed. Generally, there will be an optimal rotor diameter/rated power pairing that will maximise yield within a given set of flow conditions [33]. Examples of TS generator scale-up include OMP going from their 250KW SR250 device to the 2MW O2, Hydroquest developing their 2.5MW Oceanquest 2 device (up from 1MW seen with the Oceanquest 1), and Proteus developing the 3MW AR3000 (up from 1.5MW seen with the AR1500).

5.5.2 INNOVATION CHALLENGES AND LCOE REDUCTION POTENTIAL

Increasing the rated power of a tidal turbine, regardless of increases in rotor diameter, will lead to CAPEX increases due to the larger generator and higher rating of required power electronics. However, both cost and mass scaling are non-linear, meaning that larger devices of the same asset class will be more material-efficient and will be favourable when looking at metrics like rated capacity per tonne [33]. To ensure that increasing generator sizes can achieve optimal reliability, consideration must also be given to the increases in turbine loading as generators scale up. Improved load calculations via the use of advanced design software tools will play a key role in increasing confidence in the mechanical performance of larger turbines before they are deployed at future TS sites.

For this innovation area, final LCoE reduction was estimated at 5-10%.

5.6 CONTROLLERS THAT OPTIMISE LIFETIME TURBINE PERFORMANCE

5.6.1 BACKGROUND

Controllers are comprised of electrical control strategy algorithms that bring about a desired performance profile for a given generation asset, with the electrical control at a turbine's generator side subsequently impacting the mechanical loading and torque conditions at the rotor side. In the case of TS control strategies, they allow more efficient turbine and array operation, as well as the ability to operate in more extreme conditions. Examples of control strategies include maximum power point tracking (MPPT) which is used to maximise power generation across a range of operating conditions. In the case of a TS turbine, MPPT would seek to generate maximum power across the full range of flow speeds that the turbine is subject to.

Like turbine placement strategies which seek to optimise whole-array performance, turbine controllers go far beyond that of just yield maximisation. For the first generation of TS test turbines, the control strategies that were implemented focused primarily on load reduction to slow blade fatigue when, during this period, blade failure was the most common turbine failure mode due to the underestimation of loading conditions [31].

The problem with many previous control strategies was that the load reduction implemented also significantly reduced turbine yield. Looking to the present, the control strategies that are currently being developed in academia can reduce loading while minimising the bearing that this has on yield across the full range of flow speeds that a turbine may encounter. Examples of such control strategies include those explained to us by one academic, where the algorithms they have developed and tested seek to mitigate loading experienced by the turbine during flow speed variations. These loads can be managed through a variety of means, including the alteration of generator speed so that less energy is extracted during an increase in flow speed, and more power is produced from the generator during a decrease in flow speed [42]. Another method used to reduce loading is to use axial induction factor (AIF) control which involves changing the pitch angle and tip speed ratio of the turbine's blades, meaning that such control algorithms can and should be used together with variable pitched blades [43]. By using AIF control, torque and thrust reduction can be reduced by around 30-40% and 6-18% respectively while achieving negligible reductions in power output [44].

5.6.2 INNOVATION CHALLENGES AND LCOE REDUCTION POTENTIAL

Control strategy algorithms are currently at the lower end of the TRL scale. The control strategies described in Ref [42] and [43] were developed and tested on MATLAB, with real life testing of such control strategies only being done on a lab turbine in dry conditions to date. For next generation control strategies to progress further up the TRL scale there needs to be enough of an appetite from developers to adopt the technology on their devices (they are interested but have more urgent priorities at present).

In terms of LCoE impact, it is anticipated that reductions in the region of 5-10% can be achieved by using control strategy algorithms.

5.7 OPTIMISED FOUNDATIONS FOR FIXED DEVICES

5.7.1 BACKGROUND

Gravity based foundations at present require significant amounts of concrete and steel, and as a result are sub-optimal in terms of their design and material efficiency. Due to the size and mass of gravity base foundations they are often transported to site on large, expensive installation vessels, thus increasing installation costs. Monopile based foundations for fixed bottom devices are the most promising alternative solution to gravity bases at present, with such a solution requires far less material. Proteus Marine Renewables estimate that the adoption of monopile foundations can reduce steel requirements by 90% per foundation, thus significantly reducing foundation related CAPEX [36]. Beyond monopile foundations a range of other concepts have been investigated for fixed bottom TS devices including streamlined twin turbine foundations which were found to offer reduced hydrodynamic loading on turbines which minimised structural requirements while featuring fixation subsystems to maximise yields from oncoming tidal flows [45].

5.7.2 INNOVATION CHALLENGES AND LCOE REDUCTION POTENTIAL

There are little technical barriers standing in the way of the installation of piles which would be suitable for a range of bed mounted TS devices. However, when looking at the size of existing and scheduled TS projects, the cost differential between gravity based and piled foundations has much scope to widen. This is due to installation vessels (e.g., heavy lift vessels and jack-up barges) capable of piling fixed TS foundations currently being oversized for the scale of installation operations being considered. The costs associated with hiring such vessels for pile installation will become less of an issue as TS arrays reach commercial scale in terms of turbine volume. Looking forward, one alternative to large installation vessels could be the use of remote micro-pilling installation rigs which will be cheaper to hire and are of a more appropriate scale for the size of piles being installed [36].

In terms of final LCoE impact that can be realised via transitioning from gravity based to piled foundations, internal ORE Catapult modelling has estimated reductions of 5-10%. As for streamlined twin turbine foundations, LCoE reductions are hard to ascertain due to such an architecture having never progressed beyond design simulation over a decade ago. At the time, gravity foundations were chosen over twin tower foundations for purposes of design simplicity.

5.8 OPTIMISING & STANDARDISING WET MATE CONNECTORS

5.8.1 BACKGROUND

Wet mate connectors are used in a range of sectors including O&G, offshore wind and TS. For offshore wind and TS, wet mates are used to enable subsea connection of individual turbines to wider turbine arrays and export cables. Wet mates offer several advantages against dry mate connectors which include removing the need to bring cables to the surface for connection or disconnection, thus reducing time and costs associated with installation and maintenance. Additionally, because of quicker connection and disconnection, vessel hire periods can be reduced which allow larger weather windows in which it is safe to operate offshore. When considering wet mate installation versus that of dry mates, wet mate installation costs are estimated to be 65% lower [19].

At present many wet mates used in TS are highly bespoke. This results in far higher per unit costs for wet mates, with designs often only being suitable for one turbine model. Asides from developers using bespoke designs that will only work with their particular turbine models; low order volume is another area which results in many TS developers having to settle for sub-optimal wet mate designs. Much of this low order volume is down to the relatively nascent state of the TS industry, thus resulting in the industry having far less leverage in influencing suppliers to provide designs which are optimal for the TS sector. At present, many developers must settle with what little compatible designs are made available to them.

On the side of wet mate suppliers, they are insistent on sticking to the “classic” voltage levels (e.g., 6.6kV, 10kV) with the main reason being that they wish for their wet mates to have multi-market applications. The cost of wet mate manufacture is also reduced by sticking to standardised voltage levels as this makes it far easier for wet met suppliers to source required subcomponents such as connectors and breaker units.

There is a desire for wet mate suppliers to provide an industry-standard connector design for the TS sector. However, in the view of the supplier we engaged with, there needs to be a clear consensus from TS developers that indicates what they want from suppliers at an industry-wide level.

5.8.2 INNOVATION CHALLENGES AND LCOE REDUCTION POTENTIAL

Collaboration is required between TS developers and suppliers to aid eventual standardisation; otherwise, wet mates will be left in a state where per unit cost reductions are massively slowed. Attention needs to be given to aspects such as operating voltages and measurement equipment so that standardised designs are compatible with the maximum number of devices. To achieve this, developers will also be likely to face the requirement of changing turbine design elements on their end.

As mentioned above, order volume is hugely influential on the unit cost of wet mates which will support subsequent LCoE reductions. When speaking with a wet mate supplier they would require order volumes of at least 50 units per year to even consider serial production, which is crucial to enable any sizable cost reduction per individual wet mate. Furthermore, it would require order volumes in the region of 100 to 200 wet mates per year for said supplier to invest in machining and tooling to further streamline their serial production ability.

Regarding the effects of design optimisation on individual unit cost, the same wet mate supplier informed us that connector manufacture was reduced by 18% when specific design tweaks were implemented. Despite a considerable reduction in CAPEX, there is no information the supplier could provide us as to how this modified design would improve connector reliability and subsequent operational expenditure (OPEX) reductions through its operational lifetime, thus making an LCoE reduction figure in this instance impossible to ascertain. However, through internal modelling, an LCoE reduction of 2-5% was calculated.

5.9 CONDITION MONITORING OF CABLES

5.9.1 BACKGROUND

Effective condition monitoring (CM) of subsea cables has been of huge interest for the offshore wind industry in recent years, with subsea cable failures accounting for over three quarters of offshore wind related insurance claims in the UK, and repairs often taking months to resolve while costing operators millions in lost revenue [46]. With TS being at a far earlier stage of development, the CM of cables has understandably been less of a consideration, with turbine component cost reduction being the primary focus for many developers. However, as larger arrays come online in the later part of the 2020s, a better understanding of cable prognosis and failure modes to minimise downtime will be essential in reducing project OPEX while maximising generation hours for operators in the future.

While far less cable is used in TS projects due to the shorter distances to shore and smaller scale of projects compared to offshore wind, the conditions at TS sites are highly dynamic and have the potential to cause cable friction with the seabed, thus causing cable wear. It has been observed that such friction is particularly pronounced on rocky seabed sites [36].

When looking at CM of TS cables, there will be a great deal of knowledge transfer available from offshore wind in terms of the monitoring technology used. An example of cable monitoring technology that is being applied in offshore wind which is applicable in TS includes distributed temperature sensing (DTS) to provide depth of burial, cable exposure, and real time thermal rating calculations. Distributed acoustic sensing (DAS) can also be used to provide insights of real time abrasion or strumming of exposed cables, impact events such as strikes from anchors or fishing gear, and electrical fault detection which is in the earlier stages of development. Additionally, DAS can be aided by artificial intelligence to enable faster cable prognosis [47]. DTS and DAS have been demonstrated at the MayGen site as part of the TIGER project.

Although not specific to just cables, attention should also be given to data acquisition software packages that combine and optimise interactions between the range of CM and SCADA systems that are used on offshore wind and TS systems. When speaking to Ada Mode, a supplier of cloud based data acquisition, they informed us that collected cable data can be integrated with other parts of a wind turbine or TS system, with the wider system broken down by system areas and data tags (i.e., sensor points which collect measurements such as voltage, temperature, pressure, etc). The advantage of such a software package is that it only requires supporting sensors to integrate individual components into a whole-system condition monitoring framework. To date, Ada Mode have tested their solution on ORE Catapult’s Levenmouth Demonstration Turbine, with testing of beta systems recently being deployed on multiple wind farms in collaboration with various developers. Furthermore, work has also been carried out on OMP’s O2 turbine, with Ada Mode seeing little issue in scaling their product up or down to suit a range of offshore renewable project requirements in the future.

5.9.2 INNOVATION CHALLENGES AND LCOE REDUCTION POTENTIAL

When speaking to Marlinks, a supplier of cable integrity monitoring solutions, they stated that DAS is becoming even more common on offshore wind projects, with systems costing in the region of €150k-€230k (approximately £130k-£200k). The exact cost savings that could be expected from installing such a system from an LCoE standpoint could not be ascertained by Marlinks, but they did state that an offshore wind operator can expect to save more than ten times this value through the prevention of just one cable fault. Regarding TS projects currently in operation and those awarded a CfD at AR4, the same magnitude of savings would be unlikely to be achieved from one avoided cable fault due to far less generation loss being suffered, owing to the far smaller capacities seen in existing TS projects compared to current and future offshore farms. However, as future TS arrays continue to grow in capacity, the total achievable LCoE reductions that CM systems can offer the sector will also grow.

The way in which cable data is acquired is one of the most crucial factors in determining the effectiveness of the CM being installed. With such a high frequency of measurements being made, offshore renewable projects will require data processing and storage units as part of the wider CM system. On a typical wind farm, a DAS system can record around 1TB of data per day on average according to Marlinks. Because of this, data acquisition must exhibit a degree of selectivity so that the data collected is of use, and prevents excessively large volumes being collected to the point it becomes a disadvantage from a fault detection perspective.

Regardless of the number of potential faults that can be detected by CM, savings over the course of a project's lifetime can also be expected by virtue of ROVs no longer being required for a range of inspection activities. Depending on the regulatory landscape, the installation of depth of burial monitoring can bring about savings by removing the need for annual surveying which ensure cables are buried at a depth that adheres to statutory requirements. Marlinks stated that their depth of burial monitoring solution allowed Belgian owners of subsea cables to avoid annual surveys by sending fortnightly measurements on cable depth to regulators.

One other area where extensive CM can reduce the lifetime cost of TS projects is in the reduction of insurance costs. By combining the installation of CM alongside a well organised approach to cable maintenance, insurers will be willing to lower premiums in many instances. However, because cable CM allows project owners to better detect faults and failure modes, many insurers are becoming less willing to cover certain claims, with the onus being put on project owners to resolve potential cable failures at an earlier stage via a proactive maintenance approach due to them being sufficiently notified of potential failures well in advance. When trying to gauge the reductions in insurance premiums that can be brought about through the installation of cable CM in both offshore wind and TS projects, it is very difficult to determine as there are many factors at play that insurers must consider. Examples of these include who is financially backing a given project (e.g., private individual investors, or developers with project portfolios spanning multiple countries), the size of the project (e.g., several megawatts as seen in TS, or hundreds of MWs as seen with offshore wind), the age of the assets which are to be insured, and how the party being insured has managed risk in the past.

Focusing on the presence of dynamic cables within floating TS systems, the CM hardware provided by Marlinks would largely be the same. However, from a data acquisition point of view, the supporting modelling software will have to be tweaked so that only problematic cable movements are detected which have the potential to cause eventual faults. A degree of selectivity is required to avoid excessively high data collection rates, with much of this data being of little use as most captured movements will be benign in nature and a result of typical dynamic cable operation. Ada Mode provided a similar view in this respect.

The final LCoE reduction that could be achieved through CM of cables was estimated at 2-5% when internal modelling was used.

5.10 INDIVIDUAL PITCH CONTROL

5.10.1 BACKGROUND

Pitch control systems alter a turbine's blade angle in relation to the tidal flow. This can be done to maximise power generation, minimise loading, and assisting turbine braking systems. Pitch control systems bear some similarity to the electrical control strategies discussed earlier in Section 5.6, but instead of controlling interactions between generator electrical output and rotor torque; pitch control focuses on the angle at which each turbine blade operates.

The simplest method of pitch control is collective pitch control where all turbine blades collectively pitch together to the same angle, whereas individual pitch control (IPC) involves independently pitching each blade to its own angle. For example, the angle of individual blades may be adjusted every time it passes the turbine's support structure so that loading variations can be minimised and system lifetime eventually extended. When comparing fixed and floating devices, optimal IPC control strategies can vary. When successfully implemented on a TS turbine, optimised IPC hardware can play a role in maximising swept area for a given nacelle mass, which is crucial in enabling the use of larger rotor diameters and subsequent higher yields. By increasing turbine yield, higher capacity factors are achieved, with each 1% increase in lifetime capacity factor resulting in a LCoE decrease of around 1% [34].

5.10.2 INNOVATION CHALLENGES AND LCOE REDUCTION POTENTIAL

For IPC to fulfil its LCoE reduction potential, reliability improvements need to be made. TS pitch control designs in the past have required significant maintenance, with major failures of pitch control systems being expensive to repair, often with long lead times. In addition to this, there is also a lack of agreement on what the most important safety factors should be for pitch control design. There is also an absence of any off-the-shelf design for pitch control systems, resulting in more expensive, bespoke solutions to be used. To resolve this, developers should work with key suppliers to ensure learnings from each project are being shared at an industry level and not just at a project level so that continuous learning can be achieved [34].

If the right steps can be taken to improve pitch control systems, then LCoE reductions in the region of 2-5% can be expected.

6 TIDAL STREAM TECHNOLOGY ROADMAPS

With the LCoE reduction potential of each innovation covered in Section 5, this section provides commentary on the TRL, CRL, case for intervention, and HSE impact of each innovation (Section 6.1). As well as this, roadmap visuals which illustrate three cost reduction trajectories are presented based on the commercialisation timescale of each innovation area (Section 6.2). Finally, the limitations of relying solely on cost reduction via technology innovation is discussed with regards to achieving ~1GW of TS in the UK by 2035 as per previous ORE Catapult modelling. As such, this modelling was carried out in response to the MEC's recommendation of 1GW of marine energy is installed in the UK by 2035. Much of the commentary in this area focuses on the level of pot capacity that TS will need to secure in future CfD allocation rounds, and how the current CfD allocation structure is inadequate in enabling TS to have its maximum benefit on the wider energy system (Section 6.3). The findings in sections 6.1 and 6.2 were acquired through engagement with industry, supply chain, and internal expertise within ORE Catapult, while the findings in Section 6.3 were reached via modelling which used updated iterations of TS market growth projections from TIGER deliverables, of which these estimate cumulative UK TS capacity out to 2040.

6.1 SCORING CRITERIA OF EACH INNOVATION AREA

In this section, each innovation area is scored in terms of its potential to reduce LCoE, TRL, CRL, and case for intervention. By doing so, the extent and criticality of required technical and commercial support can be gauged going forward so that each technology can be commercialised within their anticipated timescales. Additionally, current TRLs will indicate the nature of support required to enable commercialisation. For example, if an innovation is standing at a medium TRL (TRL 4-6) then the support required may be collaboration with a research organisation (such as ORE Catapult or EMEC) so that the innovation in discussion can be proven at scale. Meanwhile, an innovation with a high TRL (7-9) may simply require the growth of an extensive TS project pipeline so that supply chain is confident in market demand and the commercial readiness is improved.

The focus of this report is centred on short to medium-term, achievable innovations, which offer the greatest LCoE reductions for TS. However, attention should also be paid to the case for intervention for each innovation area, with those scoring high in this area urgently requiring support if they are to commercialise within the anticipated timescales. Support could take the form of a joint industry project (JIP), publicly funded research, regulatory updates, or collaboration with a research organisation. Delays or failure in commercialising key technology innovations will result in a slower cost reduction trajectory which will have a significant impact on the cumulative installed capacity of TS in the UK to 2035 and beyond. With lower capacities of TS installed, this could contribute towards far higher energy system dispatch costs under a net zero scenario by 2050, due to lack of firm power and a higher reliance on expensive peaking plants, such as combined cycle gas turbines using carbon capture and storage technology.

Finally, the HSE impact of each innovation is assessed, with those scoring high offering substantial improvements in the safety of worker personnel, or in the environmental impact of future projects, that of which can support a more streamlined consenting process which has become even more important with annual CfD rounds and when looking towards arrays of 100MW and upwards. Below in Figure 8 the full scoring of each innovation area is shown.

Innovation Area	LCoE Reduction (%)	Expected Commercialisation Timescale	Current TRL	Current CRL	Case for Intervention	Health, Safety & Environmental Impact
Step Change in Rotor Diameters	20+	2023 AR4 (2027/28)	Medium	Low	Medium	Low
Subsea Hubs	10-20	2023 AR4 (2027/28)	High	Low	Medium	Medium
Array Optimisation to Minimise LCoE	10-20	2023 AR7 (2030/31)	Medium	Medium	High	Medium
Innovative Anchoring Solutions for Floating Devices	5-10	2023 AR6 (2029/30)	Medium	Medium	Medium	High
Step Change Rated Generator Power	5-10	2023 AR4 (2027/28)	Medium	Low	Medium	Low
Controllers that Optimise Lifetime Turbine Performance	5-10	2023 AR6 (2029/30)	Medium	Low	High	Medium
Optimised Foundations for Fixed Devices	5-10	2023 AR6 (2029/30)	Medium	Medium	Medium	Medium
Optimising and Standardising Wet Mate Connectors	2-5	2023 AR6 (2029/30)	High	Medium	High	Low
Condition Monitoring of Cables	2-5	2023 AR6 (2029/30)	Medium	Medium	Medium	Medium
Optimised Individual Pitch Control	2-5	2023 AR5 (2028/29)	Medium	Medium	High	Medium

Figure 8: Full scoring for each innovation area of focus

6.2 COST REDUCTION ROADMAP VISUALS

With the cost reduction ranges and commercialisation timescales of each innovation area covered in Section 6.1, the effect that these have on the cost reduction trajectory of TS out to 2035 is assessed in this section. As stated in the report methodology in Section 3, there are three cost reduction trajectories considered: a conservative, optimistic, and a mid-range. Assuming each innovation area of focus is commercialised by the time projects from AR4 (2027/2028) to AR7 (2030/2031) are commissioned, the LCoE figures given for each time period here represent the strike prices that will be made in each scenario at their respective CfD allocation rounds, held approximately 5 years prior. For example, AR7 will be held in 2025, with the strike prices that are awarded by this allocation round being reflective of the LCoE that is to be achieved for projects commissioned in 2030/2031 if they are to be commercially viable. Beyond 2030/2031, and when all innovation areas of focus have been commercialised, other factors will be at play to reach close to 1GW of UK TS by 2035 which supports a LCoE of £80/MWh being achieved under a mid-range cost reduction scenario[3]. This includes the beneficial effects of volume manufacturing continuing to play a role as larger TS arrays will be developed. Technology innovation beyond the scope of that covered in this report will also be important in reducing TS costs further. This will consist of the optimisation of existing technologies combined with the introduction of new innovations. Finally, with TS technology becoming more proven and bankable, the full benefit of resolving the non-technical cost reduction barriers mentioned in Section 0 should be experienced with project financing, insurance, and warranties all seeing significant improvements[4]. In Figure 9, the occurrence of each cost reduction enabler out to 2035 is shown, and in Figure 10, the subsequent LCoE trajectories that occur as a result of the rollout of each enabler are displayed. LCoE figures given for 2035 under each cost reduction scenario were taken from projections used in TIGER report T3.4.1 Cost reduction pathway of tidal stream energy in the UK and France [3].

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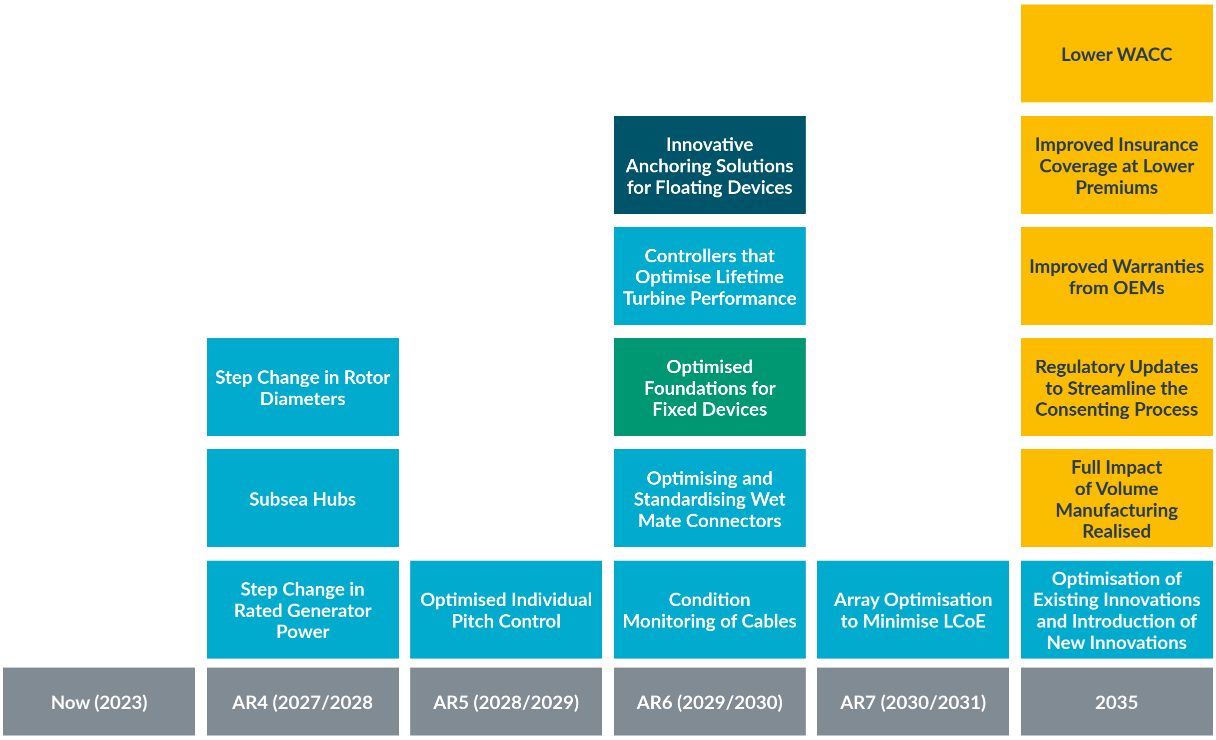
[3] Although the UK is anticipated to have the highest cumulative installed capacity of any country going forward, capacity installed elsewhere (e.g., France) will play a role in reaching £80 ± £30/MWh by 2035.

[4] The non-technical barriers discussed in this report will be gradually resolved in parallel with the commercialisation of technology innovation. However, the impact they have in parallel with technology commercialisation is not quantified in this report.



Now (2023)	AR4 (2027/2028	AR5 (2028/2029)	AR6 (2029/2030)	AR7 (2030/2031)	2035
					Lower WACC
			Innovative Anchoring Solutions for Floating Devices		Improved Insurance Coverage at Lower Premiums
			Controllers that Optimise Lifetime Turbine Performance		Improved Warranties from OEMs
	Step Change in Rotor Diameters		Optimised Foundations for Fixed Devices		Regulatory Updates to Streamline the Consenting Process
	Subsea Hubs		Optimising and Standardising Wet Mate Connectors		Full Impact of Volume Manufacturing Realised
	Step Change in Rated Generator Power	Optimised Individual Pitch Control	Condition Monitoring of Cables	Array Optimisation to Minimise LCoE	Optimisation of Existing Innovations and Introduction of New Innovations

Figure 9: Cost reduction enabler rollout: Technology applicable to fixed and floating devices (light blue), technology applicable to fixed only (green), technology applicable to floating only (blue), non-technology related enabler (gold)

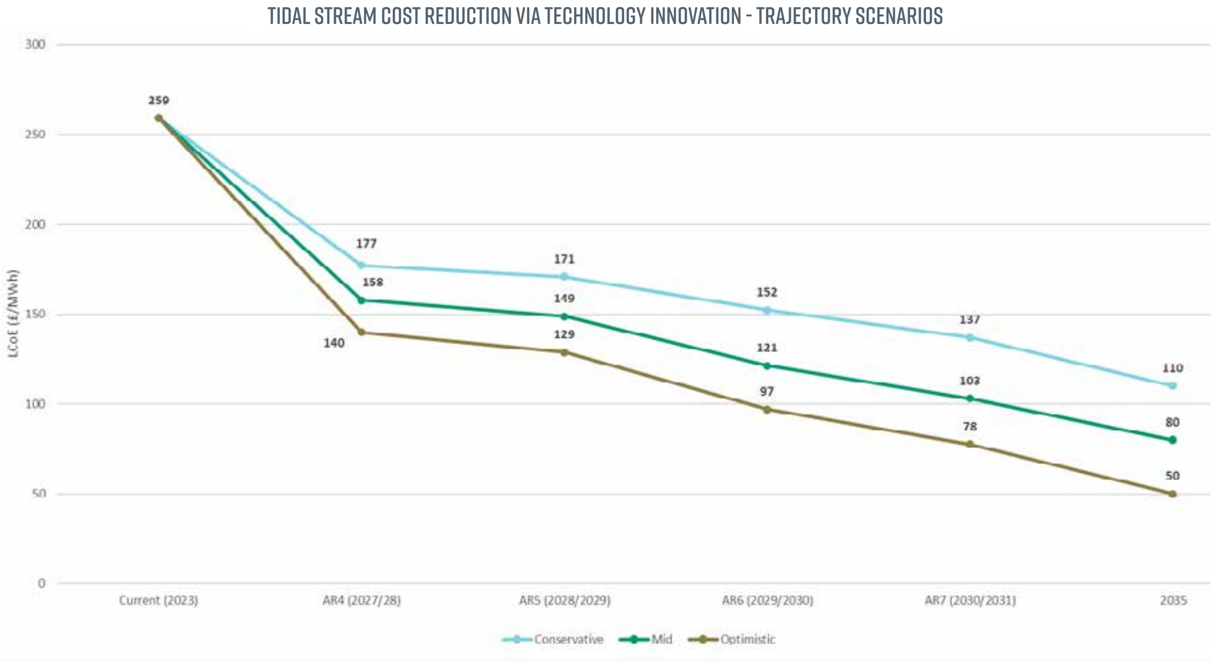


Figure 10:Tidal stream cost reduction trajectories

6.3 LIMITATIONS OF THE CURRENT CFD ALLOCATION PROCESS

When looking forward to 2035 and beyond, the amount of TS capacity that is awarded at each CfD allocation round will largely be dependent on the strike price that is awarded, and the amount of budget that is made available within the technology pot that TS is placed in, with or without a ringfence. At AR5, TS found itself in technology Pot 2 alongside less established, emerging renewable technologies such as FOW and wave, with TS being the only technology of any pot to have an allocated ringfence of £10m/year. The halving of annual ringfenced support from £20m in AR4, to £10m in AR5 meant that only ~18.1MW of TS was secured via ringfencing compared to 40.8MW in AR4, with the remaining ~35MW of capacity being awarded due to the absence of any bids for FOW projects.

When looking to AR6 and beyond, regardless of the ringfenced support that is made available, it is imperative that developers who are awarded capacity can deliver projects of the highest reliability using known turbine architectures that maximise bankability. This will have the effect of improving access to finance while proving to government that continued ringfencing at future allocation rounds is warranted. Nevertheless, if the TS project pipeline is to grow at the required pace to reach ~1GW of installed capacity by 2035, then an increase in ringfenced support will need to be provided within the next two years. But more importantly, changes to the CfD allocation process are paramount if TS is to win ever-increasing capacities within the technology pot it competes in once the technology is better established.

At present, the CfD allocation process awards capacity to projects/technologies that bid in at the lowest strike price. In the context of AR4, due to its emerging nature, TS could not successfully compete against other technologies in Pot 2, hence the requirement for a ringfenced budget. This is demonstrated by the strike prices secured by Pot 2 technologies at AR4, as shown in Table 3 [5].

Pots 2 Technology	Strike Price (£/MWh)
Tidal Stream	178.54
Floating Offshore Wind	87.30
Remote Island Wind	46.39

Table 3: AR4 strike price results for Pot 2 technologies [5]

In this section, the shortcomings of the current CfD allocation process are assessed and analysis is given as to how the current ringfenced budget is inadequate in enabling the volumes of TS capacity that need to be awarded at future allocation rounds in order to achieve a target of ~1GW by 2035. To demonstrate the impact that an improved allocation process could have; the optimistic and mid-range cost reduction trajectories from Figure 10 are used to project how much cumulative capacity can be achieved by 2040 under two scenarios which are: a proactive government response and a delayed government response (Section 6.3.1). These scenarios both assume required changes being made to the allocation process so that TS can continue to be awarded increasing amounts of capacity at future allocation rounds without the need for ringfenced support. By using these scenarios, the amount of pot capacity that needs to be awarded in monetary terms is calculated to demonstrate that a new means of awarding CfDs is critical (Section 6.3.2). Finally, changes that should be made to the existing CfD allocation process are discussed. These changes will allow generation capacity to be awarded on the basis of the whole-system and economic value that a given technology provides and not just on the strike price it can achieve (Section 6.3.3).

6.3.1 CAPACITY WON THROUGH PROACTIVE AND DELAYED RESPONSES

In this section, we look at the combined impact that technology innovation and timely government policy can have on the amount of TS capacity that is installed out to 2040. The four projections modelled here are the optimistic and mid-range cost reduction trajectories shown in Figure 10 under scenarios which entail both proactive and delayed government changes to the CfD allocation process. Such modelling demonstrates how delaying auction reform by even a couple of years can have a significant impact on the amount of TS capacity that is installed in the long-term, regardless of the extent of cost reduction enabled through technology innovation. Cumulative capacity achieved under each projection was modelled by calculating the amount of capacity that is won at each allocation round between 2024 (AR6) and 2037 (AR19), with this being based on the LCoE of TS, which is reduced over time by the ten innovation areas of focus, and the remaining cost reduction enablers displayed in Figure 9. Both of the government response scenarios and their underlying assumptions are described in greater detail below.

Delayed Government Response Assumptions:

- A baseload reference electricity price of £34.47/MWh is maintained throughout the modelling.
- TS maintains a load factor of 38.9% throughout the modelling.
- AR6 (2024) sees the same level of ringfenced capacity awarded as AR5 (18.1MW). Only ringfenced capacity is secured here. This results in a smaller amount of total TS capacity being awarded compared to AR5.
- A £10m ringfence is maintained up to AR8 (2026). Increases in awarded capacity are seen at AR7 and AR8 due to gradual reductions in TS LCoE being realised.
- TS ringfence is raised to £20m in AR9 (2027).
- The CfD allocation process is changed from AR9 (2027) onwards. Emphasis is placed on awarding projects based on whole-system and economic value.
- Ringfencing for TS is removed from AR10 (2028) as the new CfD structure allows continuous increases in pot capacity being won by TS projects (10% compounded annual growth rate out to AR19).
- Both cost reduction trajectories used consider TS capacity installed elsewhere (e.g., France).

Proactive Government Response Assumptions:

- All assumptions remain the same apart from ;
  - The CfD allocation process is changed from AR7 (2025) onwards and;
  - Ringfencing for TS is removed from AR8 (2026) as the new CfD structure allows continuous increases in pot capacity being won by TS projects.

By using the assumptions described above, the impact that these have on cumulative TS capacity under each scenario using both cost reduction trajectories could be calculated, with the results shown in Figure 11.

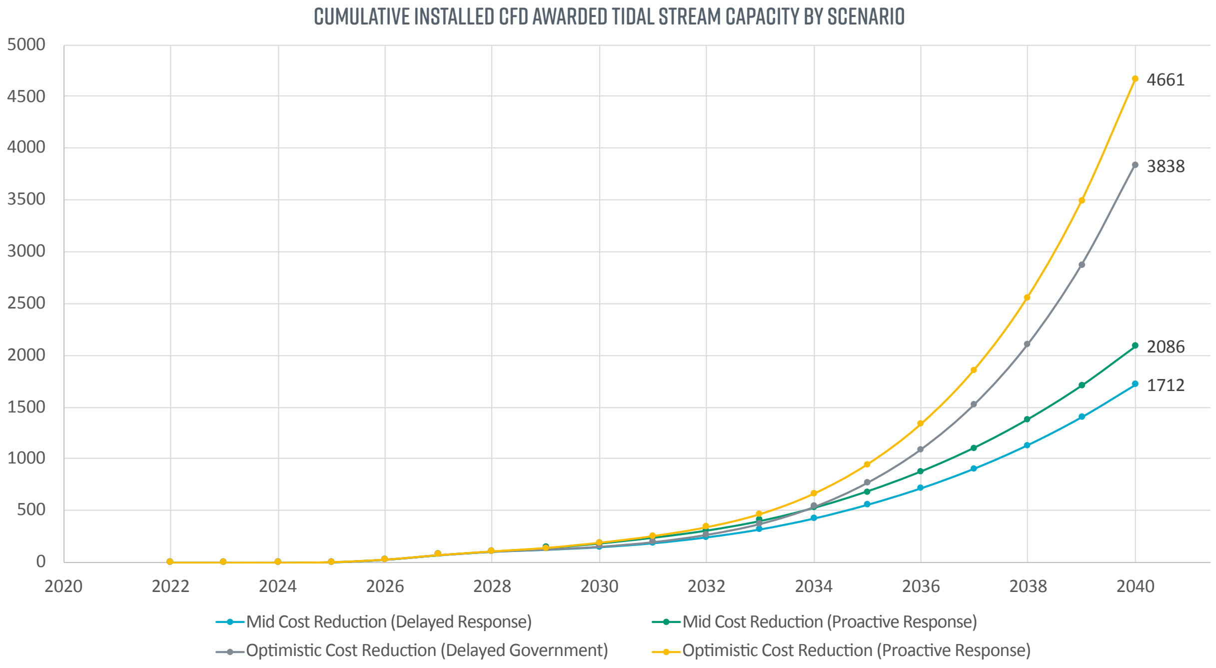


Figure 11:Cumulative CfD awarded tidal stream capacity based on technology impact and government action

From Figure 11, regardless of the cost reduction trajectory experienced, a proactive government response enables significantly more UK TS to be installed by 2040. Looking at the optimistic and mid-range cost reduction trajectories respectively, around 800MW and 400MW more TS capacity can be installed through a swifter shift to an auction model that is not focused solely on strike prices (Appendix E). Such results show that government should act quickly if TS is to maximise its potential in balancing grid generation variability while reducing peaking plant dispatch costs for the UK energy system.

6.3.2 POT CAPACITY REQUIREMENTS TO SATISFY 2040 PROJECTIONS

When a reduced ringfence of £10m/year was provided for AR5, there was concern that a continued reduction in ringfenced support over the next few years could slow the pipeline development of TS to the point where it struggles to move away from ringfencing. However, beyond ringfencing, an adequate process is needed so that greater quantities of TS capacity can continue to secure CfDs at future allocation rounds, despite the fact that TS long-term will never match the strike prices of more established technologies such as fixed bottom offshore wind, and even those of emerging technologies in Pot 2 such as FOW, hence the need for non-price factors. Below in Figure 12, the amount of pot capacity that needs to be awarded in future allocation rounds out to 2037 (AR19) is shown. These projections use the same assumptions listed in Section 6.3.1 which apply to both the optimistic and mid-range cost reduction trajectory.

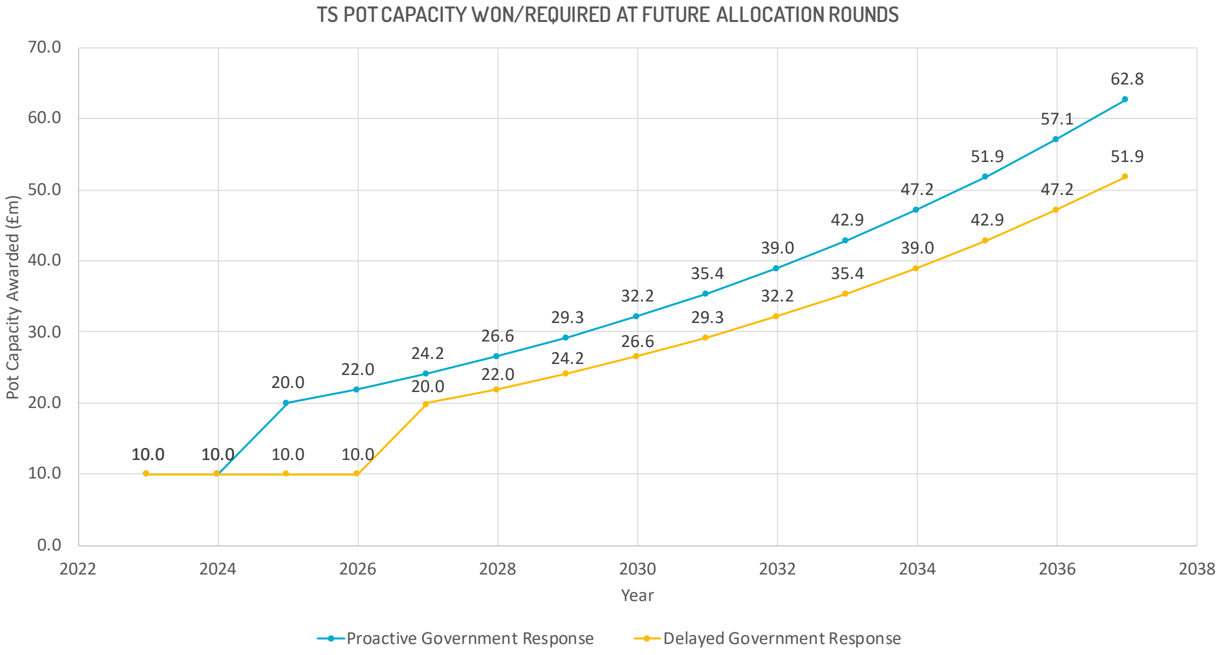


Figure 12:Tidal stream allocation round requirements in achieving 2040 cumulative capacity projections

The results in Figure 12 show that the secured pot capacity in future allocation rounds must increase substantially for an extensive TS pipeline to be formed, regardless of the cost reduction trajectory enabled by technology innovation. While an increase in ringfenced support to £20m or above can serve as a means of ensuring greater TS capacity is secured under the current allocation process over the next few years, this eventually becomes unsustainable when looking into the early 2030s and beyond. Further to this point, ringfencing will become less of an option as TS technology becomes more established, with ringfencing only typically being used as a mechanism to support emerging technologies. Therefore, changes to the CfD allocation process constitute the most effective means of achieving ~1GW of TS by 2035, with the recommended changes that are required being put forward in the following section.

6.3.3 CHANGES REQUIRED TO THE CURRENT ALLOCATION PROCESS

The current CfD allocation process is operated on a price-based criteria, with capacity awarded to projects that can bid in at the lowest strike price. This puts TS at a competitive disadvantage to technologies such as offshore wind - both fixed bottom and FOW - even after significant LCoE reductions are made through technology innovation. At present, TS capacity can only be won in the current allocation process through ringfenced support, which means that a move to non-price factors is essential to enable a project pipeline than can achieve close to 1GW of capacity by 2035. As part of the most recent Energy Security Plan published in March 2023, proposals have been made to introduce non-price factors in time for AR7 in 2025, with factors such as system integration and supply chain development being considered within this new allocation process [48].

When looking more closely at factors such as system integration and supply chain development, TS is a technology which has significant potential to fulfil both criteria. As mentioned before, research has suggested that the installation of 12.6GW of marine energy (6.4GW of wave and 6.2GW of TS) could reduce UK energy system dispatch costs by over £1 billion per annum by 2050 [15]. More specifically for TS, Imperial College London's Integrated Whole Energy System modelling suggests that annual dispatch costs can be reduced by £100m-£600m at TS LCoEs of £50/MWh and £40/MWh respectively. The far higher reductions in dispatch costs are a result of the greater quantities of TS enabled due to a £40/MWh LCoE by 2050, with additional TS generation being cheaper to run on the energy system compared to additional offshore wind which, at present, will always be favoured over TS under a price based auction criteria [2]. To help implement non-price factors, government should view TS and other generation assets which offer grid balancing capability as technologies which look not to compete with offshore wind, but instead, complement the operation of a low-cost, decarbonised energy system.

Regarding supply chain development, there is a great opportunity to achieve significant local content percentages when building an extensive TS pipeline out to 2050, with one of the key examples to date being the Orbital O2 which was built using 80% UK content [49]. With such high UK content featuring in TS turbines used in early stage deployments, this indicates that placing supply chain development commitments within the CfD allocation structure can allow TS to achieve sustainable growth in future allocation rounds when looking to achieve multiple GWs of installed capacity by 2040.

By moving to an improved CfD allocation process which considers the whole system value that TS can provide, and the opportunities for supply chain growth that emerge from supporting this growth, the advantages do not only include lower costs associated with a decarbonised energy system but GVA can be created through job creation and export potential. Regarding job creation, much of this will be in coastal communities which feeds into the just transition and supports the government's levelling up agenda that targets aforementioned communities [50].

Focusing specifically on GVA, modelling conducted by the Energy Systems Catapult and the International Energy Agency has indicated that between £2.45bn-£4.46bn of domestic GVA and between £2.5bn-£12.7bn of export potential can be created via TS deployments by 2050, emphasising the importance of exploiting the UK's first-mover advantage in the sector. To achieve the upper end of these projections, it is recommended that the government pursues an ambitious spend for domestic and international deployments while targeting high levels of UK supply chain content [51].

7 CONCLUSIONS

Through reviewing the range of TS topologies, cost reduction enablers (both technical and non-technical), specific innovations to accelerate the cost reduction journey, and reforms in the CfD allocation process that will support a sufficient project pipeline to lower operating costs for a decarbonised energy system of the future, it can be seen that the TS industry finds itself at a determining moment in its development. At such a moment, delayed or insufficient technology R&D and/or market support mechanisms can have a profound effect on the cumulative installed capacity and LCoE that is achievable in the future. Such will ultimately decide the extent of impact that TS can have in balancing a grid highly dependent on variable renewable generation. The next steps taken by government, developers and other key stakeholders can make or break an opportunity for reduced energy costs and significant economic benefit in the form of supply chain growth and highly localised job creation. This section concludes the report by setting out key recommendations for relevant stakeholders so that TS can reach its potential, and ~1GW of capacity can be achieved by 2035. Recommendations are broken down on a technical (Section 7.1) and policy (Section 7.2) basis. After the final report recommendations are given, the potential for future TS technology roadmapping activities beyond the scope of this work is discussed (Section 7.3).

7.1 RECOMMENDATIONS TO SUPPORT TECHNOLOGY INNOVATION

To support a coordinated, strategic approach to developing technology which has the greatest potential to accelerate the TS cost reduction journey, an industry-wide programme should be established that looks to commercialise and standardise common components which at present remain highly bespoke, alongside more disruptive technologies which stand lower down the TRL scale. Examples of components that would benefit under this programme include wet mate connectors, static & dynamic cables, and their ancillary components.

While components that would benefit under such a programme have not been mentioned in this report, resolution of organisational barriers such as low order volumes, a lack of component standardisation, and a lack of clarity on UK supply chain capability will play a key part in allowing a strong downward cost reduction trajectory. In terms of forming the general structure of an industry-wide TS programme, much can be learned from how similar programmes operate in other industries. For example, the Offshore Wind Growth Partnership (OWGP), which is a long-term business transformation programme that promotes closer collaboration across the supply chain. The only limitations of such a programme with regards to the innovations mentioned in this report are that they will have a high degree of commercial sensitivity with developers and thus will be harder to support directly (e.g., step changes in rotor diameter and rated generator power, array modelling to minimise LCoE).

Asides from the establishment of an industry-wide programme there is currently a range of innovation support that the TS industry can rely on in the form of academia (e.g., Supergen ORE Hub), public funding programmes (e.g., Innovate UK) and research organisations (e.g., ORE Catapult) which support targeted innovation [52]. By combining the functionalities of all mentioned organisations, the low-hanging fruit and innovation challenges which require the most urgent intervention can be best identified so that the innovation funding landscape for TS can be structured for the coming years and system costs reduced significantly.

Beyond low-hanging fruit, emphasis should be placed on developing industry-wide approaches which seek to maintain high learning rates over an extended time horizon, with the reason being to shorten the timescales in which TS reaches market parity with the wholesale market price of electricity (i.e., the point at which CfD is no longer required). By doing so, the extent of required government support through CfD is greatly reduced. For example, the Policy and Innovation Group estimate that - under the current CfD mechanism - maintaining a learning rate of 15% instead of 10% will allow wholesale market price parity to be reached by 2040, rather than beyond 2050. As well as this, the extent of CfD support required to achieve 6GW of TS by 2050 in a 15% learning rate scenario (£3.3bn) would be less than a fifth of that which would be needed in a scenario which achieves a long-term learning rate of 10% (£18.6bn) [53].

With industry programmes and innovation support helping validate the technology readiness of future TS system components, LCoE will be reduced further as more extensive insurance will be provided at lower premiums, while warranties become broader in scope and are seen as bankable by financiers. These areas serve as positive knock-on effects of cost reduction via technology innovation, while also standing as a clear indication that overall confidence in the TS sector has grown significantly.

7.2 RECOMMENDATIONS TO IMPROVE POLICY SUPPORT

As was seen in Section 6.3.1, the extent of cost reduction through technology innovation will have substantial impact on the levels of installed capacity that are feasible out to 2040 and beyond. However, even the most well-structured and sufficiently funded R&D programmes will fail to maximise their impact on the TS industry unless the appropriate policy support mechanisms are in place to complement cutting-edge technological solutions.

Firstly, a clear government target should be established for TS. This could match recommendations put forward by the MEC which advises a target of 1GW of marine energy by 2035, with most of this coming in the form of TS. Setting a clear government target sends a signal to developers and supply chain on the required scale of project pipeline, R&D funding (both private and public), and investment in manufacturing facilities needed to enable volume manufacturing of TS components and subcomponents.

Alongside a clear government target, a CRMF should also be created to set clear objectives and maintain a firm, coordinated steer on the LCoE of TS moving forward. This had a proven track record of success during the early days of fixed bottom offshore wind where ORE Catapult ran the CRMF process which guided cost reduction from an LCoE of around £140/MWh in 2012 [54], to a strike price of £37.35/MWh at AR4 (projects to be commissioned 2026/27) [5], thus representing an LCoE decrease of over 70% in around 15 years. It must be stated that the cost reduction journey of TS will differ to that of fixed bottom offshore wind due to its smaller market size and the locational limitations that it faces. Regardless of this, if a flexible and strategic approach to TS cost reduction is to be feasible then an adequately structured CRMF will play a central role in ensuring that the desired rate of cost reduction is achieved in the medium and long-term.

To support the capacity rollout that is required to meet a central government target, and to allocate the available resources to support a CRMF; moving to a CfD allocation process which focuses on non-price factors will need to be implemented. Looking further into supply chain development, doing so prevents the UK making the same mistakes it made during the early days of fixed bottom offshore wind where much of the supply chain growth was capitalised on by its European counterparts. With regards to learning from missed opportunities, much is being done to ensure that this happens with FOW, with key recommendations set out in the Independent Report of the Offshore Wind Champion [55]. Several of these recommendations bear applicability to the TS sector. These include:

- Greater emphasis from the Crown Estate and Crown Estate Scotland to include supply chain commitments as part of their seabed leasing processes.
- An updated “industrial growth plan” for offshore wind, which should be established for TS to develop a strategic “make-or-buy” approach for key areas of the supply chain which take into account the UK’s comparative advantages and opportunities for growth.
- The implementation of non-price factors in the CfD allocation process.

Beyond these measures, the establishment of a sector deal for TS - similar to what exists for offshore wind – would allow the UK's abundant tidal resource to be better utilised, and manufacturing capability to be better aligned with sectoral demand. In addition to this, a sector deal could also provide [4]:

- Greater forward visibility for the TS industry by making a central government capacity target a key pillar of the deal.
- A set government target for local content creation.
- Targets for job growth in coastal communities which have been left behind economically over the past few decades, thus supporting the government's levelling up agenda.
- Targets for maximising the export of TS products and services.

However, such a sector deal would require investment and commitment from government, project developers, and key suppliers. To keep TS sector deal ambitions on course, a programme which continuously supports the growth of the industry should be delivered, serving similar functions to what the OWGP does for the offshore wind industry.

Alongside all that has been mentioned above, measures to streamline the consenting process will also be of importance when ensuring that a growing pipeline can be sustained without numerous projects suffering major delays. Technology which maximises efficiency in data collection on the presence of marine life and their behavioural patterns will ensure TS projects can reduce their environmental impact, and if required, provide the necessary compensatory measures where certain impacts cannot be avoided. More importantly, however, will be ensuring that certain datasets can be shared and made accessible to all relevant stakeholders, while data collection approaches are standardised to simplify and speed up the consenting process for developers. To support in streamlining the consenting process at a policy level, workstreams can be initiated through a TS sector deal, like that being done in the offshore wind Sector Deal with programmes such as Pathways to Growth [56]. Additionally, initiatives similar to the Offshore Wind Environmental Evidence Register should be established to provide a foundation in improving access to species and seabed data that will allow TS developers to provide planning applications to regulators in far shorter timescales than what is currently achievable [57].

7.3 FUTURE ROADMAPPING ACTIVITIES

Beyond the scope of this report, further TS technology roadmapping activities are being considered as part of a TS Cost Reduction Monitoring Framework delivered by ORE Catapult, with the list of ten innovations covered in this report to be expanded and updated iteratively as part of a portfolio of projects, the Technology Stream Delivery Plan. By doing so, an extensive roadmap can serve as a prioritisation tool for the wider TS industry which can also play a role in coordinating the actions of a CRMF once established. As mentioned previously, part of the roadmapping work carried out in this report was based on the format and criteria found in the OWIH roadmaps. By implementing a similar approach taken with these roadmaps, a holistic view of the TS can be founded, with input into the roadmap's content coming from a combination of industry, academia, and internal ORE Catapult expertise. Furthermore, calibration into the scoring of specific innovation areas could be carried out by regular review from an external advisory group of selected experts.

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APPENDIX A

TECHNOLOGY READINESS LEVEL DEFINITIONS

Level	Explanation
TRL 1	Basic principles observed. Scientific research begins translation to applied R&D: Lowest level of technology readiness. Examples might include paper studies of a technology's basic properties.
TRL 2	Technology concept formulated. Invention begins: Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
TRL 3	Experimental proof of concept. Active R&D is initiated: This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
TRL 4	Technology validated in lab. Basic technological components are integrated: Basic technological components are integrated to establish that the pieces will work together.
TRL 5	Technology validated in relevant environment. Fidelity of technology improves significantly: The basic components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
TRL 6	Technology demonstrated in relevant environment. Model/prototype is tested in relevant environment: Represents a major step up in a technology's demonstrated readiness, which is well beyond that of TRL 5. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
TRL 7	System prototype demonstration in operational environment. Prototype near or at planned operational system: Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment.
TRL 8	System complete and qualified. Technology is proven to work: Actual technology completed and qualified through test and demonstration.
TRL 9	Actual system proven in operational environment. Actual application of technology is in its final form: Technology proven through successful operations. Includes competitive manufacturing in the case of key enabling technologies.

APPENDIX B
COMMERCIAL READINESS LEVEL DEFINITIONS

Level	Explanation
CRL 1	Developed an initial understanding of the commercial opportunity for the proposed product, process or solution. Outlining of the potential viability through using tools such as a business model canvas. At this stage market knowledge is limited or not obtained.
CRL 2	Undertaken initial market analysis of the wider market including general market structure, dynamics and segmentation, primarily via secondary research. Awareness of potential applications for the proposed product, process or solution; at this stage these ideas are often speculative and invalidated. Developed understanding of existing market offerings: their strengths, weaknesses and potential to be surpassed.
CRL 3	A deeper understanding of potential applications, market requirements, constraints and competitive technologies/solutions/products. Research is conducted through a combination of data gathering techniques (primary and secondary) to validate and verify the market. Developed product hypotheses from technology and market data analysis that align with identified market shortfalls. This may include the initial identification of targeted customer segments. Commercialisation analysis, with a heavy focus on primary research that considers both current market conditions and forecasted future requirements.
CRL 4	Refinement and verification of the product hypothesis through additional market/product analysis, including engagement with potential customers/users. Mapping of product/process/solution attributes against market needs, defining a clear value proposition. Creation of a basic cost-performance model to support the value proposition and illustrate technology advantages. Basic competitor analysis carried out. Initial value chain analysis, including the identification and mapping of potential suppliers, partners and customers. Identification of any certification and/or regulatory requirements.
CRL 5	A deeper understanding of target users/innovation application and market dynamics aligned with further product development. Comprehensive competitor analysis completed. Establishment of initial relationships with suppliers, partners and customers; all of which have provided input that has impacted product definition and proposition. Development of a basic financial model including initial projections for short and long-term sales, costs, margins etc. A comprehensive cost-performance model that further validates the value proposition and delivers an understanding of product design trade-offs. Documentation of alignment with the target market.

Level	Explanation
CRL 6	Translation of identified customer/market needs to product needs, optimising the product/solution design. Development of sales and marketing plan including documentation of full product/market requirement documents. Partnerships formed with key stakeholders across the value chain. Identified and secured trail partners/customers. Full understanding of all certification and regulatory requirements and appropriate steps for compliance set in progress. Continued refinement of financial models including cost/performance trade-offs etc.
CRL 7	Completion of product/solution design. The utilisation of first adopters/trial users. Full engagement, and product qualification, with all stakeholders; supply and customer agreements in place. Validation of financial models and projections for early and late-stage production/launch. Accommodation of all certification and/or regulatory compliance for both the product/solution and supporting operations.
CRL 8	Qualification of customers complete, and initial product/solution sales to target customers utilising developed business model and route to market strategy. Development of commercialisation strategies and approaches for large/rapid scale-up, including production and sales. Market assumptions are continually updated and validated to reflect changing market dynamics.
CRL 9	Widespread deployment is achieved and the business model is complete.

APPENDIX C

CASE FOR COLLABORATION DEFINITIONS

Level	Explanation
Low	Innovation area is expected to reach commercialisation within the projected timescale without any significant collaboration between key stakeholders being required.
Medium	Innovation area should still reach commercialisation, but some form of collaboration between key stakeholders will ensure that no major delays are experienced.
High	Collaboration between major stakeholders is critical. Without collaboration the innovation area of focus will experience major delays to commercialisation or may even fail to reach market.

APPENDIX D

HEALTH, SAFETY, AND ENVIRONMENTAL IMPACT DEFINITIONS

Level	Explanation
Low	Little to no improvements in health, safety, or environmental impact.
Medium	Some improvements in health, safety, or environmental impact.
High	Significant improvements in health, safety, or environmental impact.

APPENDIX E

CUMULATIVE INSTALLED CFD AWARDED TIDAL STREAM CAPACITY BY SCENARIO

Year	Mid Cost Reduction (Delayed Response)	Mid Cost Reduction (Proactive Response)
2022	0	0
2023	0	0
2024	0	0
2025	6	6
2026	31	31
2027	73	73
2028	107	110
2029	126	141
2030	151	188
2031	189	243
2032	246	312
2033	323	405
2034	427	531
2035	559	691
2036	718	883
2037	908	1113
2038	1135	1387
2039	1402	1710
2040	1712	2086

Cumulative Installed CfD Awarded Tidal Stream Capacity by Scenario (MW)

Year	Optimistic Cost Reduction (Delayed Government)	Optimistic Cost Reduction (Proactive Response)
2022	0	0
2023	0	0
2024	0	0
2025	6	6
2026	31	31
2027	73	73
2028	107	110
2029	127	143
2030	154	194
2031	199	258
2032	269	343
2033	374	470
2034	536	666
2035	770	949
2036	1092	1338
2037	1528	1866
2038	2109	2569
2039	2872	3492
2040	3838	4661

Cumulative Installed CfD Awarded Tidal Stream Capacity by Scenario (MW)

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