TIGER TIDAL STREAM INDUSTRY ENERGISER

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Development Fund

Cost reduction pathway of tidal stream energy in the UK and France

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Acronyms

Acronym	Description
AR4	Contracts for Difference Allocation Round 4
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CRMF	Cost reduction monitoring framework
EMEC	European Marine Energy Centre
ERDF	European Regional Development Fund
ESC	Energy Systems Catapult
FiT	Feed-in tariff
FORCE	Fundy Ocean Research Centre for Energy
IRR	Internal rate of return
LAT	Lowest astronomical tide
LCOE	Levelised cost of energy
MEC	Marine Energy Council
MEW	Marine Energy Wales
OPEX	Operational expenditure
ORE Catapult	Offshore Renewable Energy Catapult

PPA	Power purchase agreement
SER	French Renewable Trade Association
SMEIG	Scottish Marine Energy Industry Working Group
TIGER	Tidal Stream Industry Energiser Project
TSE	Tidal stream energy
WACC	Weighted average cost of capital

Executive summary

Tidal stream energy (TSE) is an exciting, emerging form of renewable energy. The completely predictable nature of the tidal resource makes TSE unique among renewables. This could give it a key place in our energy system as a highly predictable form of higher quality energy, improving energy security.

TSE is a disruptive technology with a successful and growing track record of device deployments and demonstrations in the last ten years. In 2020 the European industry hit a milestone of 60GWh of production [1]. Despite this, political support for the sector has been inconsistent. This has slowed down investment and technology development, compared to alternatives like solar and offshore wind that have benefited from significant public development funding and energy generation subsidy. Consequently, there has not been the chance to unlock cost reduction through deploying commercial scale arrays, and there are only a handful of projects across the UK and France to date as markets merge across the globe

Despite the historically challenging headwinds, the industry has still shown significant cost reduction ability. In 2018 ORE Catapult estimated TSE levelized cost of energy (LCOE) at £300/MWh. In the UK in 2022, four projects (40.8MW) were awarded CfDs at £178/MWh[1], to commence operation between 2025-27. This indicates an LCOE reduction exceeding 40%[2] with little to no revenue support since 2016.

While the high predictability of TSE warrants a pricing premium, due to the lower costs incurred in the wider energy system, it is crucial that TSE continues to drive down costs to become competitive with other forms of energy. In this report we analyse the cost reduction pathway of TSE considering the UK and French markets. The main aim of this work is to:

Assess and quantify the cost reduction trends being seen in the tidal industry using recent knowledge captured from the Tidal Stream Industry Energiser (TIGER) Project and other sources.

Using data from TSE technology providers and the ORE Catapult Analysis and Insights Team, we have created an industry representative LCOE trajectory. This is shown below. It considered three leading utility scale device concepts and nine cost scenarios in total, which were analysed to devise an appropriate LCOE trajectory. The key LCOE estimations are as follows:

- Currently we estimate TSE LCOE to be £259±30/MWh
- By 2026 TSE LCOE will fall to £193±48/MWh

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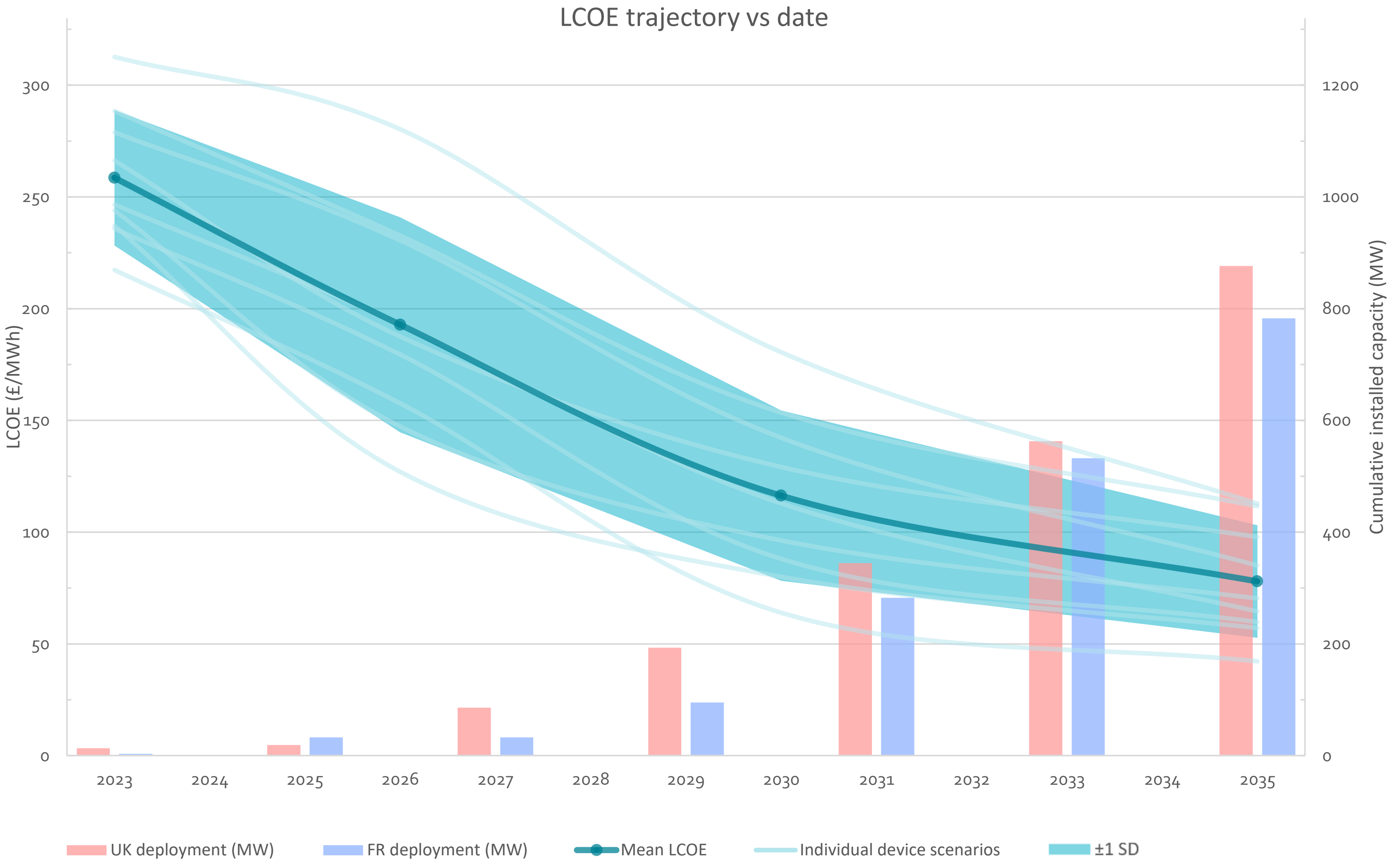
[1] Both this and ORE Catapult estimation in 2012 currency, the current base year for CfD strike prices.

[2] CfD strike price will be above the actual LCOE as it includes the return for the project developer.



UK and French TSE market projection and associated LCOE trajectories for the three devices and nine cost scenarios examined.

- By 2030 TSE LCOE will fall to £116±38/MWh
- By 2035 TSE LCOE will fall to £78±25/MWh

These estimates assume cumulative TSE deployment of 877 MW in the UK and 783 MW in France by 2035. The UK estimate echoes the sentiment by the UK Marine Energy Council (MEC), who are calling on the UK Government to set a target of 1GW of marine energy by 2035. The French estimate mirrors the current ask of French suppliers to the government.

As well as the LCOE trajectory, this report also promotes additional TSE benefits to advance the economic narrative. These have been sourced from both TIGER and third party projects, and are summarised by the following key messages:

- *Cost reduction mechanisms*: In the report we describe the key cost reduction drivers for the TSE sector. These will help the industry reach its £78±25/MWh by 2035 potential. Key areas identified include larger rotor and rated power devices (38% LCOE reduction), economies of volume from larger farms (28-50% LCOE reduction) and reduction in WACC (20% WACC reduction leads to 10% LCOE reduction).

  Within a separate TIGER study, described in this report, we identified eight cost reduction drivers that could reduce LCOE by a combined 67.5%. Assuming a present day LCOE of £259/MWh, these together would take LCOE down to £84/MWh and are achievable by 2035.

  Longer term we predict that TSE could reach £60/MWh by 2042 and £50/MWh by 2047.

- *Socioeconomic benefits*: TSE offers significant socio-economic benefits. TSE farms are more energy dense than offshore wind, meaning that farms can be more compact which reduces issues with other sea users. Socioeconomic benefits include high local content on projects (80%+), high job creation per MW (more FTEs per MW than offshore wind) and £5-19Bn in GVA by 2050. The UK also has the ability to capture 25% of international market value through exports.

- *Energy system benefits*: The completely predictable nature of TSE is perfect for a role in the energy system, reducing costs associated with curtailment, and the need for reserve gas capacity as a result of supply/demand mismatch. TSE has the ability to displace both fossil fuels and other forms of renewable energy.

  A study funded through TIGER has estimated that TSE could provide £100-600M in cost savings in the energy system per annum by 2050. It could also reduce CCGT gas capacity by 40% in the net zero energy system.

  The EVOLVE project is examining similar issues. Initial results indicate that 1GW of wave and tidal could save £114M per annum in the energy system as the diversity in the energy mix means that supply better matches demand.

From this study we recommend the following to policymakers in the UK and France:

- **Commit to industry deployment targets**. We endorse the MEC's ask of UK Government to commit to a target of 1GW of marine energy by 2035. TSE could make up 850-950MW of this. We also endorse the deployment targets (equating to 750MW by 2035) being discussed with the French Government.

- **Ensure TSE has secure route to market**. In the UK we support maintaining the current TSE ringfence in upcoming CfD rounds. In France we support the ongoing discussions between project developers and regulators.

- **Streamline consenting processes.** Reducing approval times to one year, as is being pursued for offshore wind in the UK, will strengthen the project pipeline and ensure that the next generation of projects are built. The indication is a 6-year timeframe in France between next generation projects being awarded and commissioned, which we also think could be shortened over time.

All three of these actions will improve private sector confidence, open up new funding streams for TSE and greatly accelerate the cost reduction process.

1 Introduction

1.1 Motivation

All over the world, governments are in the process of decarbonising their energy systems to counteract climate change. Many countries, including the UK [2] and France [3], have pledged to reach net zero greenhouse gas emissions by 2050. This is aligned with the conditions of the 2015 Paris Agreement which was signed by 190 countries. To reach this target it is crucial to build a robust, resilient electricity market largely free from fossil fuel sources.

In the UK, as for many developed economies, the share of renewable electricity has dramatically increased in recent years. The growth of installed renewable capacity between 2000 and 2018 grew from 1.4 GW to 42.1 GW, a 21% CAGR [4]. This increase has been dominated by wind and solar. For example, in 2020 wind and solar produced 28% of the total electricity generated, up from 2.7% in 2010 [5].

The global success of these renewable technologies has been enabled by several factors. The most significant is the plummeting costs of both technologies. The offshore wind sector has benefitted from increasing turbine size and rated power which has reduced the cost per MW installed via improved economies of scale. Competitive auctions, for example the contracts for difference (CfD) mechanism in the UK, have proved very successful in pushing costs lower and reducing uncertainty for project developers and investors by providing a stable revenue stream. In addition, improvements in financing arrangements (such as improved access to insurance and lower interest debt) has enabled lower levelized cost of energy (LCOE).

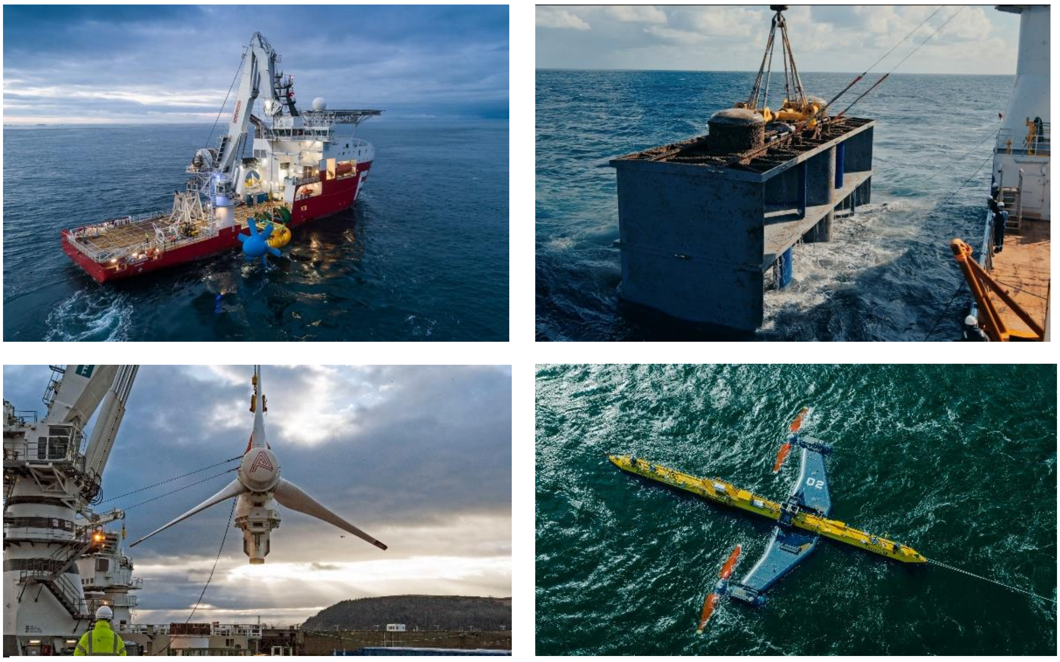


Figure 1 – Devices from four of the leading tidal stream device developers. Top-left: SIMEC Atlantis AR1500; Top-right: Orbital Marine Power O2; Bottom-left: Sabella D10; Bottom-right: Hydroquest OceanQuest.

As well as these established renewable technologies, there is increasing interest in earlier stage technologies that can provide additional and complementary benefits. One such technology is tidal stream energy (TSE). Devices consist of fully submerged rotors that rotate with the flow of water. Four of the leading TSE devices are shown in Figure 1.

Studies have estimated that 11.5 GW of tidal stream could be deployed in the waters of the UK and Channel Islands [6]. The practical resource could equate to 34 TWh/year, equal to 11% of current electricity demand. In France, the Marine Energy Observatory have estimated the practical TSE capacity at 4.5GW [7]. This is consistent with historic estimates of 3-5GW published by French transmission system operator RTE [8].

Tidal stream is a highly promising technology for a number of reasons:

- The industry is on a steep cost reduction trajectory despite a historic lack of revenue support and low number of devices deployed. While the current LCOE is higher than alternatives[3], the market is large enough that the LCOE will reach competitive wholesale market prices if the industry follows a similar trajectory as has been seen for other renewables.
- The tidal resource is completely predictable and can be forecast hundreds of years into the future. This makes tidal energy very well suited to a role in the future energy system as it reduces curtailment, supply/demand mismatch and reserve capacity requirement. This ultimately reduces the cost of the whole energy system.

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[3] As evidenced by the CfD AR4 results announced in July 2022: £178.54/MWh clearing price for tidal stream, vs £45.99/MWh for solar and £37.35/MWh for offshore wind [95].

- The resource is also completely decoupled from wind and solar energy, with regular daily peaks. The recurring cyclical power generation profile gives TSE significant synergies with battery storage as the generation profile ensures batteries will stay topped up and mitigate against deep discharge.
- There are strong domestic supply chains in the UK and France. Recent projects have been manufactured and deployed with 80-90% local content, for example the 2021 deployment of the Orbital O2 device at the Falls of Warness site [9]. There is also a significant export potential for both the UK and France, given the fact that most technology developers are located in these countries.

Policymakers have made clear that TSE needs to bring cost of energy down to a level where it can provide value for money. There is also acknowledgement that this is a young and emerging industry that needs support to achieve this goal. This is reflected in the European Commission's Strategic Energy Technology Implementation Plan (SET Plan) for Ocean Energy. Originally published in 2017, this stated a target of €100/MWh by 2030 [10]. The SET plan was revised in 2021, affirming an intermediate target of €150/MWh by 2025 and deployment targets of 100MW of marine energy (wave and tidal) by 2025 and 1GW by 2030 [11].

This report assesses the benefits of TSE, with particular emphasis on the cost reduction trajectory, to put into context the role that TSE can play in the UK and French energy systems.

1.2 Previous outlook

In 2018, the Offshore Renewable Energy Catapult (ORE Catapult) published a report that presented an LCOE outlook for the TSE sector [12]. This included a trajectory to estimate how the LCOE could be expected to fall with increasing deployment, shown in Figure 2, and an analysis of the GVA and FTE jobs that would be created. The high-level conclusion was that:

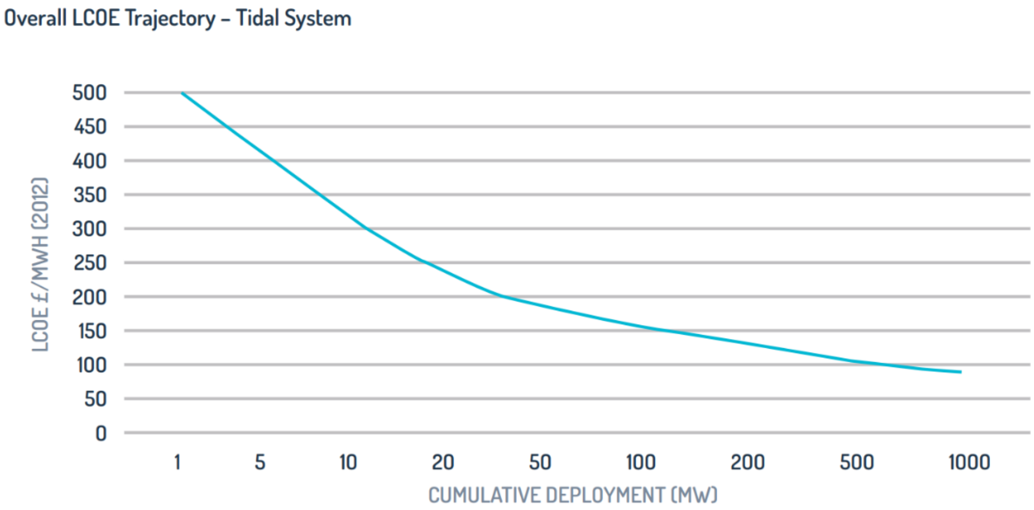

Figure 2 – Levelised cost of energy (LCOE) trajectory with cumulative UK deployment, as devised by ORE Catapult in 2018.

"Tidal stream has potential to reach a LCOE of £150 per MWh by 100MW installed, reducing to £90 per MWh by 1GW and £80 per MWh by 2GW. Further reductions are possible with additional focus on innovation and continued reductions in cost of capital towards levels coming through in offshore wind."

The study has been cited numerous times by industry and since its publication has served well as a point for the industry to rally around. This study has been designed as an update to the 2018 report, incorporating recent developments and knowledge.

1.3 Aim and objectives

The aim of this work is to assess and quantify the cost reduction trends being seen in the tidal industry using recent knowledge captured from the Tidal Stream Industry Energiser (TIGER) Project and other sources.

It has been designed to provide an up-to-date assessment, building on the previous ORE Catapult work from 2018, and map out a third party, credible cost reduction pathway for the sector.

The report attempts to meet the aim through achieving the following objectives:

- Devise a new LCOE trajectory, based on up-to-date evidence, representative of TSE technology targeting the wholesale market.
- Describe recent developments in the tidal stream sector in the UK, France and rest of world to put this work in context.
- Showcase key findings from TIGER and other projects that help to advance the cost reduction narrative.
- Encapsulate the wider tidal stream narrative by including commentary on additional benefits, including socio-economic benefits, local content and energy system benefits.

This work has been funded and delivered through the TIGER Project. While emphasis is on the UK and French markets, as these are the focus of TIGER, the analysis and insights are designed to be representative of the global industry.

1.4 The TIGER Project

TIGER is a €48.4M project with 68% of this funding from the European Regional Development Fund via the Interreg France (Channel) England Programme.

The aim of TIGER is to accelerate innovation, cost reduction and supply chains in the tidal stream sector by supporting six projects in the Channel region (between the UK and France). It is a highly collaborative project, bringing together 18 project partners. These include research centres, turbine technology developers, project developers and academia.

More detailed information about TIGER can be found in Appendix A.

1.5 Report structure

This report continues in *Chapter 2* by examining the current state of the sector. This includes commentary on the leading device concepts, markets and progress since the previous 2018 Catapult cost reduction study.

Chapter 3 presents our updated LCOE trajectory for the industry, formulated using real cost data from technology providers.

Chapter 4 discusses the wider benefits and advantages of the tidal stream industry including local content, socio-economic benefits and energy system cost savings from the highly predictable energy source.

Chapter 5 summarises the conclusions and key messages of the study.

Chapter 6 finishes with recommendations for policymakers.

2 Current state of the sector

This section summarises the current state of the tidal stream industry. This includes an overview of the technologies, main markets and projects.

2.1 Technologies

Table 1 shows the market leading technology providers and their devices at the present time. These have been categorised according to rated power, foundation type and operating principle.

While the industry has seen high convergence towards horizontal axis concepts, mirroring the wind energy industry, there are developers working on vertical axis (notably Hydroquest) and other types of power take-off entirely (such as kites).

Some providers are working on micro-scale devices for run-of-river. These can be classified as sub 100 kW with the main markets being remote communities and off-grid systems. For example ORPC's RivGen was deployed in 2019 and has been used to power a remote village in Alaska. The scale of these units means that successive generations can be tested and deployed quickly using small and readily available vessels. While costs are relatively high for the energy they produce, the price of energy in the typical target markets is also higher as it can be expensive to transport traditional fuels like diesel to such remote locations.

In recent years the majority of technology providers have been developing small to mid scale devices in the 0.1-1 MW range. This type of device gives a good compromise between power production and upfront capital cost. Devices can be produced and installed in the single millions of pounds, compared to potentially tens of millions for larger devices, so these projects are more suitable for grant funding. There are also shallow water locations (less than ~30m LAT) where utility scale device would not be suitable as clearance is needed above and below the rotor.

Table 1 – Leading tidal stream providers (bold) and devices, categorised by scale and foundation type/operating principle. Black entries are devices that have seen real world deployment. Blue text are devices in development.

	"Microscale" <100 kW	"Small scale" 100 kW – 1 MW	"Utility scale" >1 MW
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 **SIMEC Atlantis (GBR)** AR500 **Verdant Power (USA)** TriFrame Gen5 **Hydrowing (GBR)** HW500, HW1000	**Andritz Hydro Hammerfest (AUT)** Mk1 1.5MW turbine **SIMEC Atlantis (GBR)** AR1500, AR2000, AR3000 **Hydrowing (GBR)** HW1500
Fixed foundation Vertical axis turbine	**Instream Energy Systems (CAN)** 25 kW 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
Floating foundation Horizontal axis turbine		**Orbital Marine Power (GBR)** SR250 (ScotRenewables) **Sustainable Marine (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)	

Smaller devices do have advantages, especially regarding O&M. Devices that are able to use smaller, more readily available vessels, have particular advantage at the present time due to the energy crisis being witnessed in 2022. The high price of oil and subsequent increased activity in the O&M sector has had the effect of pushing up vessel spot prices and reducing vessel availability [13] [14].

Lastly, there are companies who are developing devices at larger utility scales. These have the advantages of larger rotor swept area and economies of scale which ultimately results in a lower LCOE. This is evidenced by the recent CfD round in the UK (more details on this are provided in Section 2.2.1) where all of the tidal stream CfDs were secured by utility scale suppliers. While cheaper on a per MW/per MWh basis, these devices represent larger capital investments and so greater financial support is required to deploy arrays.

2.2 Tidal stream markets

2.2.1 UK

The UK is the leading tidal stream market in the world. As previous mentioned, it is estimated that 11.5GW of TSE capacity could be deployed in the UK and Channel Islands [6], with the ability to supply 11% of the UK's electricity demand. There is good geographic spread: with suitable project locations in England, Wales, Northern Ireland and Scotland. The latter country is home to the European Marine Energy Centre (EMEC), the world-leading test centre where full scale tidal turbines can be deployed in real sea conditions[4].

Government support for TSE has been varied. Prior to 2016, several sites were awarded revenue support via the Renewables Obligation (RO) scheme. This changed in 2016: the RO was replaced by the Contracts for Difference (CfD) mechanism and TSE had to compete with more established technologies. As a result, In subsequent years TSE was unable to access revenue support, limiting deployment to single turbine demonstration projects.

Perception of TSE has become much more positive in recent years. Significant contributing factors have been high profile technology demonstrations as well as the improved organisation of the sector, for example the work of groups such as:

- Marine Energy Wales (MEW), founded in 2016.
- The Scottish Marine Energy Industry Working Group (SMEIG), founded in 2017.
- The Marine Energy Council (MEC), founded in 2018.

The MEC, made up of leading marine energy developers, has been particularly instrumental in linking industry to government and educating about the wider benefits of sector support. This has included engaging with ministers via APPG meetings. A notable activity was organising a trip to EMEC for the Energy Minister at the time, Anne-Marie Trevelyan, to see tidal devices in person [15].

In 2021 interest in the sector also grew due to rising oil prices and increased emphasis on energy security. The predictable nature of tidal stream is a key advantage, and is discussed in Section 4.3.

In November 2021 it was announced that the tidal sector has secured a £20M per annum ringfence within CfD Allocation Round 4 (AR4). There were four successful bids with a total capacity of 40.8 MW and at a clearing strike price of £178.54/MWh (15% below the administrative strike price set for TSE) [16]. These projects, shown in Table 2,

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[4] For more information visit https://www.emec.org.uk/ (accessed 08/08/2022)

are planned to be commissioned between 2025 and 2027. This will take the UK capacity with revenue support from 10.4 MW today to 51.2 MW by 2027, a 400% increase.

Table 2 – The four successful projects that secured CfDs in Allocation Round 4.

Project developer	Site name	Location	Project size (MW)	Anticipated technology	Anticipated turbine rating	Commissioning year
SIMEC Atlantis	Meygen	Scotland	28	Fixed	2	2026/27
Magallanes Renovables	Morlais	Wales	5.62	Floating	1.5	2025/26
Orbital Marine Power	Eday 2	Scotland	4.8	Floating	2.4	2026/27
	Eday 1	Scotland	2.4	Floating	2.4	2026/27

2.2.2 France

France is a leading market for tidal stream. Studies have estimated that 3-5.5 GW of capacity could be deployed [17] [18]. The most promising area is the Raz Blanchard, between the Normandy coastline and the Channel Island of Alderney, with an estimated 2 GW of capacity [19]. Some studies have estimated that the capacity in this region, also considering the territorial waters of Alderney, could be as high as 3.9-5.1 GW [20].

Plans for commercial tidal developments in the Raz Blanchard were made in 2013. Two lease applications were submitted and granted: one by ENGIE and one by EDF Renewables. In 2020 these were transferred to Normandie Hydroliennes and Hydroquest respectively [21]. These companies are in the process of modifying their lease terms: increasing their pilot farm capacities to 12MW[5] and 17.5MW[6] respectively. Both companies plan to commission these farms by 2025/26, subject to funding.

France is home to several leading test sites. SEENEOH operate a test site in Bordeaux and support EDF at the Paimpol-Bréhat site, which has been converted into the largest TSE test site in France. In April 2019 French developer Hydroquest installed their 1MW OceanQuest device at Paimpol-Bréhat for approximately 29 months, funded through the TIGER project [22]. The site is undergoing infrastructure and connection improvements, for example in September 2022 the subsea cable was upgraded to a new drymate cable which allows devices to be installed without the need for divers [23].

ADEME, the French Agency for Ecological Transition, has historically funded TSE projects and research via grants. There is a stage gate approach from ADEME whereby a project

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[5] https://simecatlantis.com/tidal-stream/raz-blanchard/ (accessed 17/10/2022)

[6] https://www.hydroquest.fr/en/flowatt-en/ (accessed 17/10/2022)

must secure capital grant first and then feed-in tariff (FiT) discussions can commence. There is no formal revenue support mechanism for TSE in France, but Normandie Hydroliennes and Hydroquest are in bi-lateral discussions with the French government to support their Raz Blanchard projects. This process is supported by the French Renewable Trade Association (SER). French industry would like the government to commit to 2.5GW of future tidal stream tenders. This capacity would be auctioned off between 2025 and 2033 in three phases, with focus primarily on the Raz Blanchard.

2.2.3 Canada

Canada is a strong supporter of TSE and has been for some time. The main markets are large utility scale projects, most notably in the Bay of Fundy, and for small scale, run of river turbines for remote communities.

The Bay of Fundy in Nova Scotia is the largest tidal range in the world. Studies have indicated that 2.5GW of power could be extracted with less than 5% change in the tidal amplitude, with a potential maximum of 7 GW [24]. The key issue for Canada is improving grid infrastructure to cope with the potentially GW of TSE production available in remote regions far from transmission grid.

The Fundy Ocean Research Centre for Energy (FORCE), located in the Minas Passage, was established in 2009 and is a test site for early commercial devices and arrays. Devices that have been deployed include OpenHydro (2016 & 2018), BigMoon Power's Kinetic Keel (2018) and Sustainable Marine's PLAT-I (2017 and 2022). The site has 30MW of capacity allocated which will be deployed over the coming years [25].

The province of Nova Scotia has offered a feed in tariff (FiT) to tidal developers for several years. Three projects planned at FORCE have 15-year agreements: Sustainable Marine's Pempa'q Project (9 MW), BigMoon Power (9 MW), and DP Energy's Uisce Tapa project (9 MW) [26]. These projects have FiTs of CAD$530/MWh [18], equivalent to £343/MWh (as of July 2022).

2.2.4 Rest of world

As well as the above, other notable countries include the USA, China, Indonesia and Japan. Interesting recent TSE projects across the world include:

- Verdant Power's TriFrame deployment in New York East River, including a world first testing of thermoplastic tidal blades [27].
- Minesto's Dragon Class D4 kite deployment in the Faroe Islands, including a PPA signed with the electric utility company SEV [28].
- Several demonstration turbines in China from LHD, ZJU University and China Three Gorges, among others.
- SIMEC Atlantis AR500 deployment in the Goto Islands, Japan [29].

2.3 Tidal turbine deployment timeline

Figure 3 is a timeline showing global tidal stream turbine deployments since 2016. The timeline also shows anticipated turbine deployments out to 2027 where known.

The turbine deployments are categorised according to location, technology type, rated power and whether the projects have known long term revenue support via the CfD or RO mechanism.

2.3.1 2016

In 2016, the first tidal stream arrays were deployed. Most notable were the 6MW Meygen array, still the largest tidal turbine array in the world today, and Nova Innovation's Shetland Tidal Array. Both UK projects receive ROCs under the RO scheme, which was fully replaced by the CfD scheme in April 2017 [30]. As previously mentioned, 2016 saw the removal of a 100MW CfD ringfence for wave and tidal [31]. This meant that tidal stream had to compete with much lower cost offshore wind, effectively ending access to revenue support.

2.3.2 2017

There were few deployments in 2017. This was a combination of developers focussing on operating the large amount of technology deployed in 2016 and uncertainty caused by the CfD ringfence removal. Notable in this year was Nova Innovation's expansion of the Shetland Array and the testing of a 650kW turbine by Zhejiang University (ZJU) [32]. ZJU have been an active part of China's TSE industry, testing various devices at different scales from floating platforms since 2004.

2.3.3 2018

2018 saw the liquidation of OpenHydro, announced by their parent company Naval Energies just days after their turbine deployment at the FORCE test site in Canada [33]. In 2020 it was announced that BigMoon Power would take over the berth at FORCE, with a power purchase agreement (PPA) of CAD$475/MWh, but on the condition that they remove the existing OpenHydro machine from the seabed [34].

This year also saw installations from developers who went on to become prominent names in the sector: Sustainable Marine's PLAT-I installation at FORCE, Sabella's D10 deployment at Ushant Island (France) and Minesto's DG500 deployment at Holyhead Deep (Wales, UK).

2.3.4 2019

2019 saw notable demonstration turbine deployments at test sites. French developer Hydroquest installed their vertical axis OceanQuest device at Paimpol Bréhat with funding from the TIGER project. Spanish developer Magallanes Renovables installed their floating 2 MW ATIR platform at EMEC for testing as part of the Ocean 2G project, funded through the EU's Horizon 2020 programme [35]. Lastly, Minesto redeployed their DG5000 device for further testing at Holyhead Deep.

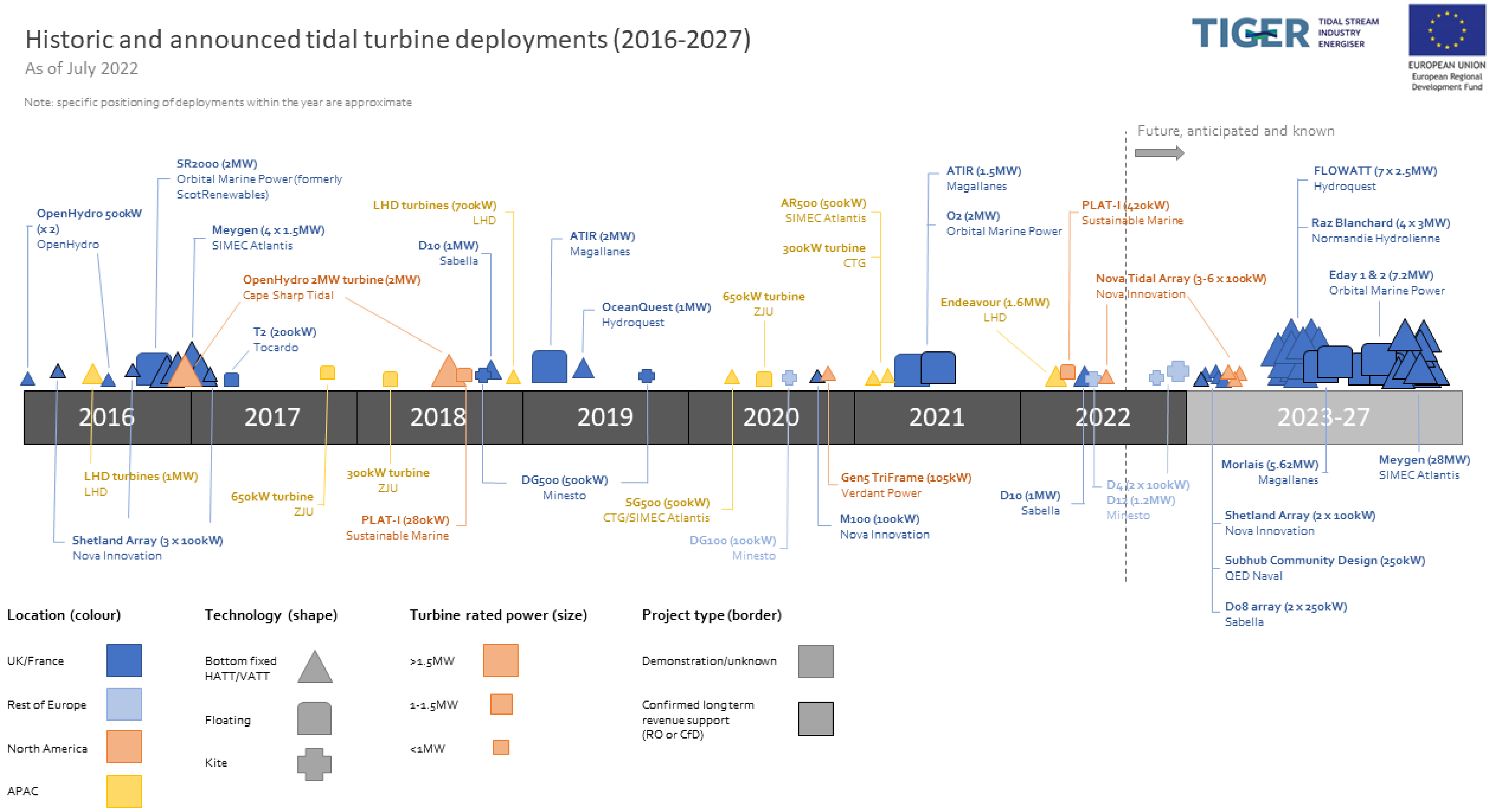

Figure 3 – Historic and upcoming tidal turbine deployments. Shapes (each representing a single turbine deployment) are categorised according to location, technology type, rated power and whether the project has ongoing public revenue support

2.3.5 2020

2020 was characterised by smaller scale device deployments. Minesto deployed their DG100 at the Faroe Islands, paving the way for future projects. Nova Innovation expanded their Shetland Tidal Array with a fourth turbine, their first direct drive turbine.

Verdant Power's installed their TriFrame in New York East River. SIMEC Atlantis also shared their knowledge with China Three Gorges, a major state-owned Chinese power company, who collaborated on a 500 kW turbine.

2.3.6 2021

2021 saw renewed interest in the tidal stream sector with a step-change in turbine size. The Orbital Marine Power O2 was installed at the Falls of Warness site in July, the site with access to revenue support via ROCs. This 2 MW device is designed to operate for the next 15 years, and the company proclaimed it as *"the world's most powerful tidal turbine"* [36]. This year also saw Magallanes upgraded ATIR platform deployed at EMEC and SIMEC Atlantis's deployment of a 500kW turbine in Japan.

These high-profile deployments, as well as the successful projects witnessed in earlier years, helped to improve the image of the industry which had historically been seen as expensive compared to alternatives. This contributed to the success of the industry in securing UK CfD revenue support in 2022 which has resulted in 40.8MW of new tidal capacity announced (see Section 2.2.1).

2.3.7 2022

So far 2022 has seen some very interesting turbine deployments. The 1.6 MW Endeavor, manufactured by LHD in China, has been touted as the largest Chinese tidal turbine produced and shows that the industry is gaining traction [37]. This takes the capacity of the LHD Zhoushan tidal power station to 3.3 MW (adding to deployments in 2016 and 2018), with plans to expand further to over 7 MW.

In Canada, Sustainable Marine deployed their 420kW floating platform, complete with four Schottel rotors. This was the first floating tidal device to export power to the Canadian grid [38] and has revenue support via a PPA.

Sabella redeployed their 1MW D10 device at Ushant Island for further testing. This was part funded within the TIGER project.

Minesto completed designed of their new "Dragon Class" tidal kite, stating improved performance and lower costs. They deployed the 100 kW D4 at the Faroe Islands and plan to follow this up with a second 100 kW and a 1.2 MW device later in the year.

As of August 2022, Nova Innovation are also preparing to install their first turbine in the Petit Passage in Nova Scotia (the Nova Tidal Array project), following this up with 2-5 more turbines in 2023. The ultimate aim is to deploy a 1.5 MW array.

2.3.8 2023-2027

As well as Nova Innovation's array at FORCE, the company are also planning to add additional turbines into their Shetland Tidal Array in 2023. Other array projects planned for 2023-24 include Sabella's 2 x 250 kW array in the Morbihan Gulf, France, and QED Naval's 250 kW (3 x 85 kW) Subhub deployment at Yarmouth Harbour, UK. Both of these projects are awaiting decisions on consenting.

In 2025 both Hydroquest and Normandie Hydroliennes (a JV including turbine supplier SIMEC Atlantis) plan to install projects in the Raz Blanchard, France, totalling 29.5 MW. Both projects are in the consenting stage and discussions are ongoing with the French regulator over revenue support.

The 40.8 MW allocated in the UK's CfD Allocation Round 4 (AR4) will be deployed in 2025-27. All of this capacity is expected to be utility scale turbines (2MW+), with a mix between fixed and floating devices.

2.3.9 Summary

As can be seen, there was a flurry of activity in 2016, especially towards the end of the year, with most of the turbine deployment in the UK. Tidal stream lost access to revenue support in 2016, the UK favouring technology agnostic CfD auctions, which meant that the sector was unable to compete with more established renewables. This led to a quiet few years with a focus on demonstration and testing of smaller scale prototypes (<1MW).

2021 was a landmark year for the sector, with two utility scale floating device deployments (Magallanes ATIR and Orbital O2) and the announcement of a ringfence for the sector in UK AR4. The 40.8 MW of capacity announced in the UK in 2022 is anticipated for 2025-27 and could be the start of a new commercial era for TSE.

2.4 Research projects and grant funding

Some of the aforementioned device deployments have been assisted by grant funding schemes. A summary of recent and ongoing grant funded projects is shown in Table 3. As well as TIGER, previously mentioned, other prominent projects include:

- *The Morlais project* in Wales secured €37.6 M of ERDF funding from the EU, administered by the Welsh European Funding Office (WEFO). This funding is being used to develop site infrastructure, including onshore transmission and civil works, and is likely to be the last EU grant-funded UK project.
- *The FORWARD-2030* project is being led by Orbital and is exploring integration of their floating device with hydrogen production and battery storage. This also includes deploying a second turbine at their Falls of Warness O2 site.
- *EnFAIT* (Enabling Future Arrays In Tidal) is being led by Nova Innovation. The project is investigating different array layouts and studying wake effects by repositioning turbines at their Shetland array.

- *Carbo4Power*, led by National Technical University of Athens, is exploring advanced blade materials for wind and tidal turbines. The nano-engineered hybrid materials have the potential to improve both operational performance and blade durability while lowering cost of energy.

Table 3 – Examples of current tidal stream government funded projects that are ongoing. [1]Funded through the European Regional Development Fund (ERDF). [2]Funded through the Horizon 2020 programme.

Project/scheme	Total amount	Timeframe	Funding body	Tidal technology providers	Themes
TIGER [39]	€45.4M	2019-23	EU[1] (€30M)	• Minesto • Orbital Marine Power • QED Naval • Sabella • SIMEC Atlantis	• Deploying technology • Improving supply chain • Cost reduction
Morlais [40]	€37.6M	2022	EU[1] via Welsh Government	None (directly)	• Site development • Onshore infrastructure
FORWARD-2030 [41]	€26.7M	2021-25	EU[2] (€20.5M)	Orbital Marine Power	• Deploying technology • Hydrogen production • Volume manufacturing
EnFAIT [42]	€20M	2017-23	EU[2] (€14.9M)	Nova Innovation	• Array layouts and wake interactions
Carbo4Power [43]	€7.8M	2020-2024	EU[2] (€7M)	Sabella	• Advanced blade materials
SELKIE [44]	€5.2M	2020-2023	EU (€4.2M)[1]	None	• Software tools
ELEMENT [45]	€5M	2019-23	EU[2]	Nova Innovation	• Control systems • AI
NEMMO	€5M	2019-22	EU[2]	Magallanes Renovables	• Blade design and materials
Saltire Tidal Energy Challenge Fund [46]	£3.4M	2019	UK (Scottish Government)	Orbital Marine Power	• Deploying technology
OPIN [47]	€2.6M	2018-22	EU[1] (€1.5M)	None	• Creating industry networks
VOLT [45]	£2M	2021-23	UK (Scottish Government)	Nova Innovation	• Volume manufacturing
EVOLVE [48]	€1M	2021-23	EU[2]	Orbital Marine Power	• Energy system impact

The research covers the full value chain: from manufacturing and materials science through to software tool, control systems, technology deployments and energy system analysis.

The EU is set to continue grant funding into tidal stream with four ocean energy calls announced in the draft Horizon Europe work programme. This follows a call in early 2022 for *Demonstration of innovative rotor, blades and control systems for tidal energy devices*. It is still unclear as to whether UK-based companies will be able to bid for future Horizon grants, with a decision expected in late 2022/early 2023. UK Treasury has committed to guaranteeing funding for any EU funded project which is contracted before the end of Dec 2022.

2.5 Private sector investment

Historically the tidal sector has utilised public grant funding for deploying technology demonstrators. Recently there has been an increase in other funding streams, including crowdfunding, green bonds and debentures.

Technology developers that have secured funding via crowdfunding include:

- Orbital Marine Power secured £1M in crowdfunding in less than a week in 2020 [49]. The campaign was hosted on Crowdcube, with over £2M raised at the end of the campaign, with the company giving away 5.41% in equity [50].
- Nova Innovation: Campaigns have included a 2019 campaign, whereby the company raised £1.1M (£500k originally targeted) [51], and more recently in 2021, where the company raised over £2M on Seedrs platform (£1M originally targeted) [52].
- QED Naval: The company raised over £1M in March 2021, on Seedrs crowdfunding platform, from an initial target of £350k [53]. The final offering was 7.69% equity.

Some firms have secured debt financing by issuing bonds:

- SIMEC Atlantis raised £3.79M by issuing a bond on the Abundance crowdfunding platform in 2020, at an 8% interest rate and reaching maturity in 2024 [54]. This followed a £4.95M raise in 2017, via two bonds.
- Orbital Marine Power raised £7M in 2019, also via the Abundance platform. This was the largest amount raised on the platform at the time. Debentures of 2–5 year duration were offered, at interest rates of up to 12% [55].

  In 2022 the company completed another debenture offering, raising £4M via a 12-year debenture offering [56].
- In 2022, Sabella raised €2.5M by issuing bonds on the GwenneG platform at an 8.5% yield [57].

The certainty that revenue support offers unlocks more favourable funding streams. This has been seen recently with the 2021 Orbital Marine Power O2 deployment. Because of the consistent revenue support that the project is forecasted to generate through the RO scheme, the company were able to secure £4M of funding from the Scottish National Investment Bank to support ongoing maintenance of the turbine [56]. Orbital Marine Power noted that:

"This investment recognises the role tidal technologies can play in delivering clean, predictable energy and aligns with the [Scottish National Investment] Bank's mission to support Scotland's transition to net zero energy. The Bank's investment in this emerging technology also demonstrates its role as a development bank in attracting additional commercial funding to new markets." [56]

As tidal technology becomes further de-risked, and projects get larger, companies will have better access to lower interest debt financing. This will lower the weighted average cost of capital (WACC) of projects, increasing future cashflows and project profitability.

2.6 Summary

Since ORE Catapult's 2018 TSE update, there have been notable industry successes including:

- In the UK, a new generation of tidal stream projects are being supported with £20M allocated in 2022 CfD AR4 (40.8 MW of capacity receiving CfDs of £178.54/MWh). This includes a mix of floating and fixed devices. The four projects aim to be installed between 2025 and 2027.
- Elsewhere in the UK, Orbital Marine Power installed their O2 at the Falls of Warness site. The 15-year deployment receives revenue support via RO and has attracted investment from the Scottish National Investment Bank.
- There has been notable progression of the French tidal market, with both Hydroquest and Normandie Hydroliennes developing sites in the Raz Blanchard. This 29.5 MW of combined capacity could be deployed in 2025/26 if revenue support can be agreed.
- The market is ramping up in Canada at the FORCE test site. In 2022, Sustainable Marine exported power to the grid from a floating tidal device for the first time in Canada. Projects from DP Energy, Sustainable Marine, Nova Innovation and BigMoon Power have PPAs in place, with 30MW allocated at FORCE.
- A significant amount of money has been invested into R&D projects via grants. This includes the TIGER project (€45.4M total), FORWARD-2030 (€26.7M total), EnFAIT (€20M total) and Carbo4Power (€7.8M total). Support has also been provided to assist commercial projects and deploy technology. Examples include EU ERDF funding for Morlais (€37.6M) and the Saltire Tidal Energy Challenge fund from the Scottish Government to Orbital Marine Power (£3.4M).

3 Cost reduction pathway

In this section we present an interpretation of the current TSE cost reduction landscape. We describe where the industry is currently at, in terms of LCOE, describe the key innovations that will unlock future cost reduction and present an LCOE trajectory to map how the LCOE will reduce going forward.

3.1 Current LCOE

3.1.1 Previous estimates

While there has been notable convergence in the TSE industry in recent years there are still a variety of different device concepts (as described in Section 2.1). This makes it difficult to define a representative LCOE for the industry as it is strongly influenced by both the device and the site.

In the previous ORE Catapult TSE cost reduction assessment, as introduced in Section 1.2, we estimated an LCOE of £300/MWh in 2018. This was formulated through engagement with several TSE technology suppliers with devices concepts at various scales. It was a representative industry average derived by giving larger weighting to more recent TSE projects. Since this study there have been new studies providing estimates of LCOE:

- In February 2019, Deliverable D3.9 from the EnFAIT project was published entitled *LCOE & Financial Models* [58]. Led by Wood Group, the study assessed the LCOE pathway of TSE to understand when it would become commercially viable.

  The LCOE for pre-commercial demonstrator projects was estimated at €345-520/MWh for 1.5-2MW turbines and €472-784/MWh for sub 1MW turbines. For first of kind array installations the LCOE dropped to €262/MWh for 2-10MW farms, and dropped again to €160/MWh for 20-200MW farms. These were derived assuming conservative learning rates of 10% in CAPEX and 7% in OPEX and an 8% discount rate.
- In October 2019 BEIS published the *Tidal Stream Energy Needs Assessment*, the work led by Vivid Economics. It stated a £300/MWh LCOE estimate for fixed tidal stream and a £200/MWh LCOE for floating tidal stream. The floating number is lower than we would have expected at this time and we have not been able to validate it.
- IRENA in their 2020 report *Innovation Outlook: Ocean Energy Technologies* estimated a range of USD $0.2-0.45/kWh (about £158-355/MWh in £2021). The authors note that:

  "Due to the relatively early life-cycle stage of all ocean energy technologies, their LCOEs are difficult to predict and uncertain."
- In 2021, Coles et al. estimated the LCOE reduction seen in recent years for operational projects [6], using insights from the ORE Catapult cost reduction study

[12]. The authors derived an LCOE of about £240/MWh in 2021 and noted an approximate 25% reduction in LCOE after the first 8MW was deployed in the UK.

3.1.2 Our LCOE trajectory

Using TSE cost and yield estimates from TSE technology developers we have calculated a representative baseline LCOE trajectory to guide the industry. To do this we modelled three leading utility scale device technologies:

1. A fixed bottom horizontal axis turbine.
2. A floating horizontal axis turbine.
3. A fixed bottom vertical axis turbine.

We considered baseline, optimistic and pessimistic scenarios for each technology. These were to capture uncertainties in specific cost components, financial parameters (e.g. WACC) and variations between potential sites. For the starting point we considered hypothetical "present day" projects, considering the costs if projects were to be built in 2022/23.

We calculated future LCOE projections for each technology/scenario combination using a learning rate-based approach. We modelled technology-specific capacity buildout for the UK, France, Canada and "rest of world" and assumed learning rates in the range 13-17% across the scenarios.

The result was nine individual LCOE trajectories. We examined the mean LCOE and the standard deviation between the scenarios to indicate the uncertainty and range that could be expected between different technologies, markets and individual sites.

A more detailed description of the methodology can be found in Appendix C.

LCOE trajectory over time

Figure 4 shows the nine individual LCOE trajectories[7], including the mean and standard deviation, for the baseline market scenario. The associated UK and French cumulative deployment trajectories are also shown. The present-day (2023) mean LCOE for the scenarios examined was found to be £259/MWh, with a standard deviation of £30/MWh. It should be noted that this is a hypothetical scenario. It does not include the upcoming innovations and cost reduction drivers that will be seen for upcoming UK AR4 projects.

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[7] Note that the individual trajectories are anonymised to preserve commercial confidentiality. LCOE is also presented in £2012 real terms as this is the current CfD strike price baseline.

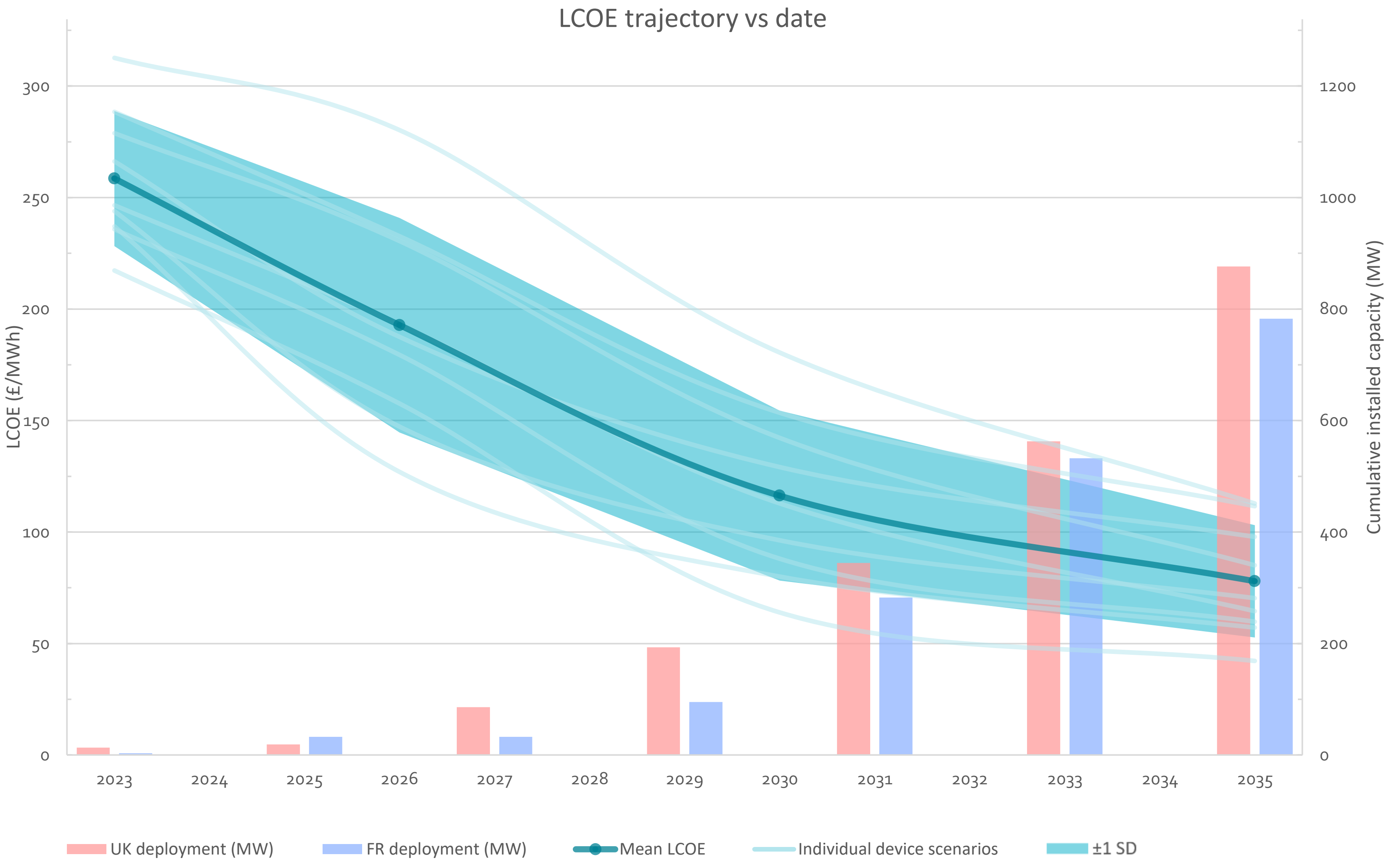

Figure 4 – UK and French TSE market projection and associated LCOE trajectories for the three devices and nine cost scenarios examined.

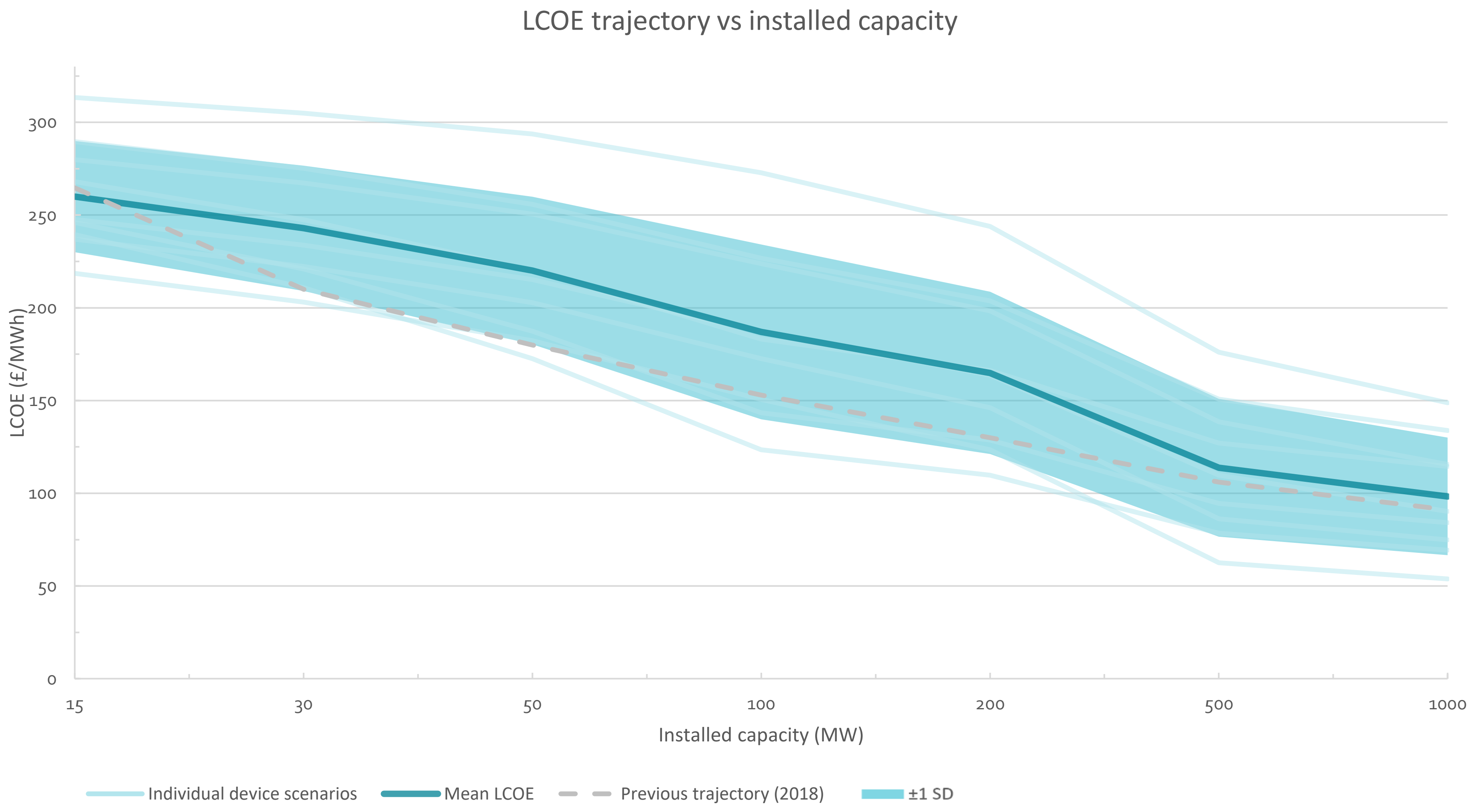

Figure 5 – LCOE trajectory vs installed capacity for the nine scenarios, considering the UK and French market. The previous trajectory derived by ORE Catapult in 2018 is also shown.

By 2026 we predict a mean LCOE of £193±48/MWh. This is above the £178/MWh AR4 strike price and can be explained by two reasons:

1. The three AR4 projects have benefitted from previous investment into grid infrastructure (at Meygen, Morlais and EMEC) and are fully consented. Our numbers represent new projects and total lifetime project cost, assuming that such activities have not been carried out.
2. Our reference scenarios include both UK and French projects. The French market is less mature than the UK, and hence including the French scenarios does increase the blended LCOE by 15%.

The range between projects is significant, from £127/MWh for the cheapest device in the optimistic case to £280/MWh for the most expensive device in the pessimistic scenario. The mean was chosen as the basis for our trajectory as this offers the fairest and most representative industry picture.

Based on our analysis we forecast representative LCOEs in 2030 and 2035 to be £116±38/MWh and £78±25/MWh respectively. This is assuming global deployment of 730MW by 2030 and 2.6GW by 2035.

LCOE trajectory vs deployed capacity

Figure 5 shows the LCOE trajectories compared to cumulative installed capacity as forecasted for the UK and France. This can be equated to individual country ambitions, for example if the UK were to deploy 1GW in isolation.

By 1GW installed in the UK and France we predict that LCOE will have fallen to £98±32 /MWh. This aligns with the £90/MWh as devised in the previous ORE Catapult study. In our baseline forecast we predict that this milestone could be reached between 2032 and 2033.

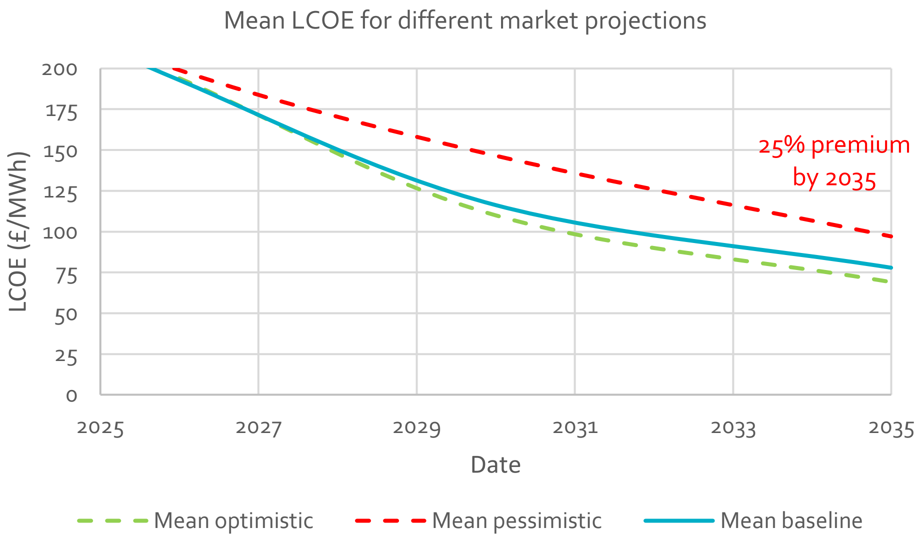

Figure 6 – Sensitivity of mean LCOE to optimistic and pessimistic market projections.

Sensitivity of LCOE to market forecast

Our baseline market forecast assumes a global installed capacity of 2.6 GW by 2035, equivalent to a 39% CAGR. This is comparable to the global trend historically seen for offshore wind (for example the IEA calculated a 30% CAGR between 2010 and 2018 [59]).

We examined the sensitivity of the nine scenarios to the global market forecast. We considered optimistic and pessimistic cases, estimated at 3.4 GW and 1GW respectively.

Figure 6 shows the sensitivity of mean LCOE to market deployment. For the optimistic scenario, mean LCOE reduces to £70±20/MWh by 2035: a decrease of 11% compared to the baseline. Conversely, for the pessimistic scenario, mean LCOE would increase to £97±25/MWh by 2035: an increase of 25% compared to the baseline. This asymmetric risk/reward profile illustrates why the sector needs front loaded revenue support to aid deployment and drive down LCOE. To enable the cost reduction process it is crucial to get devices in the water early.

3.2 Short to medium term cost reduction mechanisms (2022-2035)

TSE has strong cost reduction mechanisms in the short to mid term. As the industry is still at an early stage, devices have been historically over-engineered to demonstrate proof of concept and ensure operability. As the sector continues to commercialise, we will see costs come down as devices are optimised for minimising cost and maximising revenue. There is also high potential to reduce costs through economies of volume: mass producing successive generations of devices and introducing more automation in the manufacturing approaches.

In the period up to 2030 the following areas will offer greatest potential for LCOE reduction:

- **Larger rotor diameter and device rated power:** Larger rotor diameter devices have a larger swept area, improving energy capture. This can be augmented by increasing device rated power which allows more energy to be captured at rated flow speeds. Research from TIGER has calculated that LCOE could be reduced by 38% when considering 3MW, 26m rotor diameter turbines compared to 2MW, 20m turbines [60]. This magnitude is reflected in other studies, for example Coles and Walsh estimated that deploying AR2000 turbines at Meygen compared to AR1500 would reduce LCOE by 20%[8] [61].

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[8] AR1500: 18m rotor diameter, 1.5MW rated power. AR2000: 20m rotor diameter, 2MW rated power.

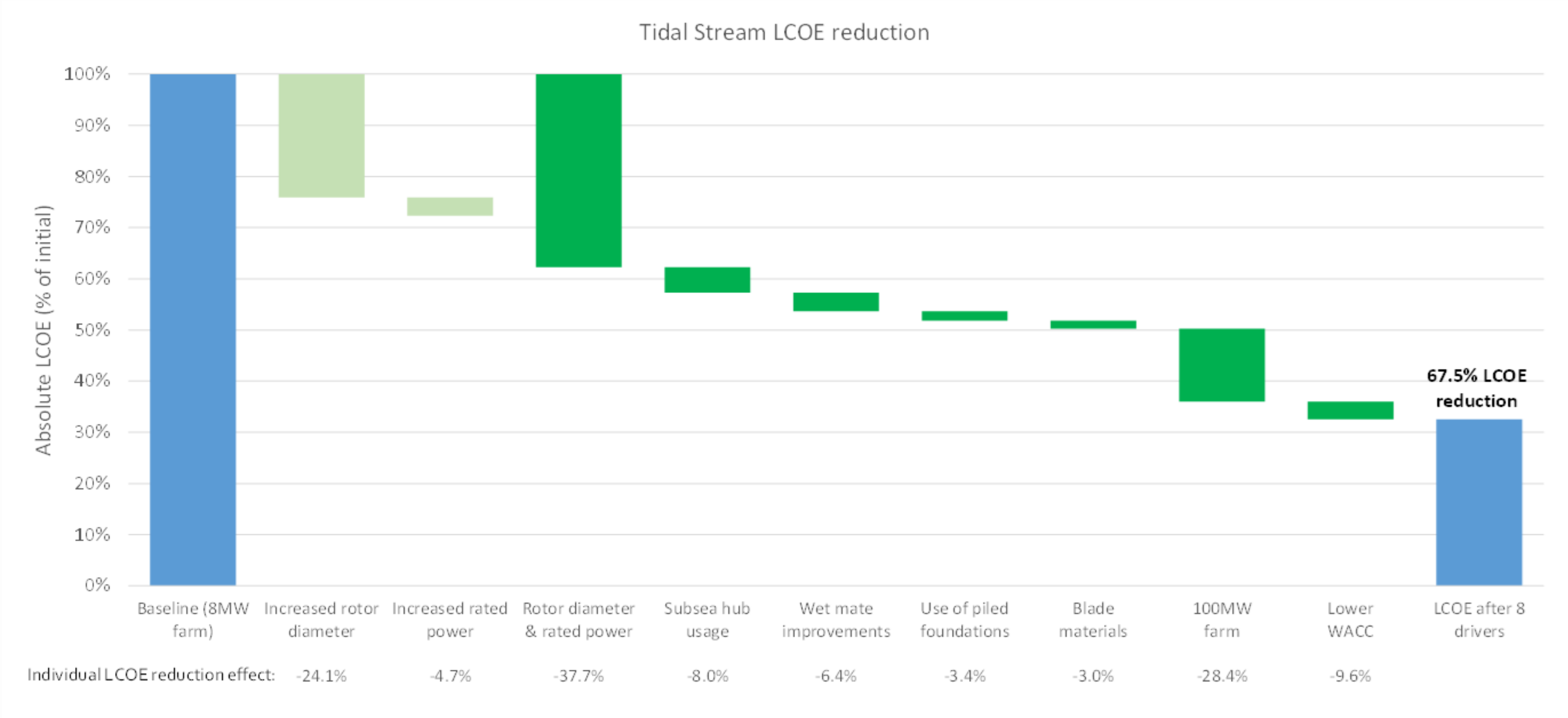

Figure 7 – LCOE reduction that can be achieved by eight cost reduction drivers. The increased rotor diameter and rated power represents the additive nature of the two previous innovations (in lighter green).

- **Economies of volume from larger farms:** Larger farms will drive down component costs through greater purchasing power and economies of volume. Fixed costs, for example associated with vessel mobilisation and onshore substation integration, are spread over more devices. This results in a decrease in the cost per MW installed.

  The LCOE reduction in going from 2-10MW to 20-200MW projects was estimated at 40% by Wood in their report for the EnFAIT project [58]. Research from TIGER has estimated a 28% LCOE reduction when increasing farm size from 8MW to 100MW [60].

- **Reduction in WACC:** As commercial projects become larger and more numerous, it will be easier to attract lower interest rate financing through debt (as opposed to equity, which has been more common to date). Banks and investment firms will be more willing to lend to TSE as the technology becomes increasingly de-risked, lowering the WACC associated with projects. Access to CfD will also give projects stable revenue and reduce risk, giving third parties more confidence to lend. Reducing WACC from 8% to 6.4% (a 20% decrease) would reduce LCOE by 9.6% [60].

- **Piled foundations:** There is an increasing trend in fixed foundations towards piled solutions (monopiles and pin piles). While TSE sites tend to be rocky, hence would require drilling, piles are much lighter and easier to assemble and transport than gravity base foundations. Piled foundations can also be deployed at more locations as they are less sensitive to seabed gradients.

  Data from TIGER partners has indicated that piled foundations would use 90% less steel than equivalent gravity base foundations [62]. This would equate to 75% cheaper foundations resulting in a 3.4% LCOE reduction [60].

- **Innovative anchors and mooring system designs:** There are several cost reduction drivers accessible to floating device types. These include innovative low-profile anchors (e.g. rock bolt anchors, Raptor anchors); mooring line materials and dampers to reduce loads and maintenance requirements; and optimised mooring arrangements whereby mooring lines are shared between multiple

  Initial feasibility studies by TIGER partners have indicated that rock bolt anchors and mooring dampers could reduce LCOE by 9.5% and 0.4% respectively[9].

- **Advanced rotors and blades:** TSE blades are one of the components that could benefit most from innovation. Ongoing research areas include advanced blade materials (for example thermo-plastic blades [27]); individual blade pitch control to improve yield and reduce loads in extreme conditions; and simpler, easier to

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[9] Estimate from TIGER partner.

manufacture blade designs of less pieces. Advanced blade materials could reduce LCOE by 3% [60] and individual pitch control by 6.4%[10].

- **Powertrain:** Turbine suppliers are focussed on improving the modularity of powertrain systems to improve ease of access for O&M. Some developers are also transitioning to direct drive turbines to improve system reliability. For example, Nova Innovation showcased a direct drive generator on their fourth Shetland Array turbine which reportedly "slashes the cost of tidal energy by a third" [63].
- **Next generation materials:** The need for improvements in materials has been identified as a key R&D focus area by entities such as the U.S Department of Energy [64] and ETIP OCEAN [65]. The former organisation, via the Water Power Technologies Office, hosted a workshop in late 2021 with over 100 participants to understand how material and manufacturing could be improved. Priority areas identified included coatings and slippery materials to reduce biofouling, tougher resins to improve blade strength and lower cost manufacturing processes.
- **Improvements in marine operations:** To date there has been limited TSE operating experience in the marine environment. In the coming years, with the next raft of commercial projects scheduled for 2025-27 in the UK, there are opportunities to improve understanding. These include vessel chartering strategy, amending procedures or equipment to increase vessel working conditions (and length of weather windows) and changing turbine design and reducing mass to improve ease of operations. Onshore there are also opportunities to improve inventory management, including management of spare parts and optimisation to reduce excessive inventory build-up.

Within a separate TIGER project deliverable (T3.2.2) we assessed eight cost reduction drivers to identify the impact on LCOE. These included larger rotors, higher rated power, advanced blade materials, piled foundations and wet mate connector improvements. We found that the eight drivers could reduce TSE LCOE by 67.5%, as shown in Figure 7. Almost 40% of the reduction comes from increasing the rotor diameter and rated power which have a compounded effect greater than the sum of the individual innovations.

3.3 Longer term cost reduction potential (2035+)

Figure 8 shows longer term forecasts beyond 2035 under different market CAGR and cost learning rates. Starting from the baseline of £78/MWh by 2035 we believe that £60/MWh could be reached by 2042 and £50/MWh by 2047. This could be accelerated if market growth is quicker than anticipated and if learning rates can sustain 17% as has been calculated for the early industry [6].

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[10] Estimate from TIGER partner.

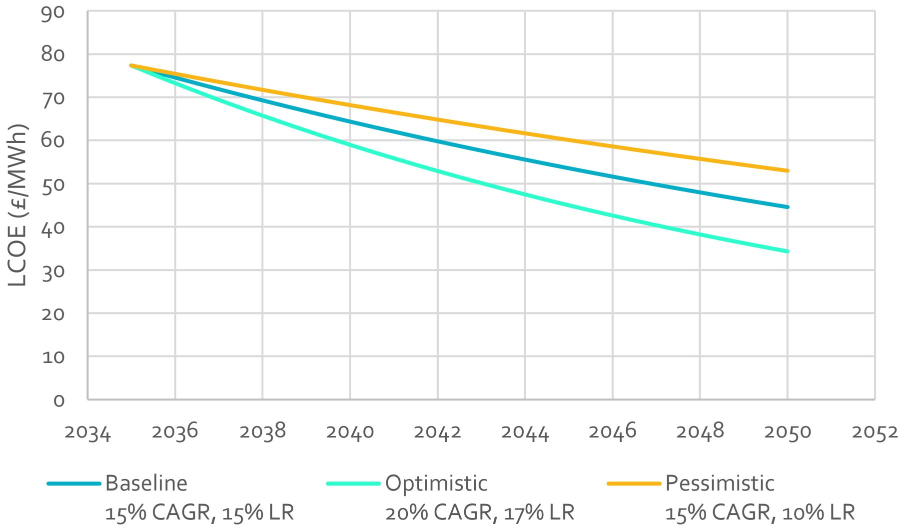


Figure 8 – Potential LCOE trajectories beyond 2035 under different CAGR and learning rate (LR) assumptions.

The CAGR and learning rates assumed are comparable to those that have been seen for more established technologies, for example the long term learning rate of offshore wind has been calculated at 14% [66].

The main cost reduction mechanism in offshore wind has been increasing turbine scale. This route is less viable for TSE as sites are constrained by the water depth, limiting the size of the rotor that can be deployed. Instead, we believe that long term cost reduction will be driven by increased economies of volume and manufacturing improvements, with a highly automated manufacturing process. The relatively small footprint of tidal turbines, compared to e.g. wind turbines, will enable large and compact farms. Optimization of array layouts, potentially utilising local blockage effects to improve energy extraction, will further drive down LCOE.

Within the market there are opportunities for both bottom-fixed and floating devices as both have their merits (for a comparison see Appendix B). Despite this, we also expect to see greater convergence in device concepts, as has been seen for offshore wind, as competitive auctions will drive the market towards a smaller number of solutions. This will reduce the bespoke nature of TSE components and establish TSE turbines as “off the shelf” systems.

We also see a place for low flow and run of river devices which would increase the size of the market above the ~11.5 GW and ~4.5 GW that have been estimated for the UK and France respectively. The industry is naturally gravitating to the higher resource sites initially, as was also the case for the wind industry, but low flow sites will become more viable as the technology matures and the commercial proposition is suitably de-risked.

The cyclical and predictable tidal resource is also well suited to a role in the energy system. TSE systems can be paired with e.g. battery storage or hydrogen production capabilities to improve the commercial offering and open up new markets. Such energy system benefits are discussed in Section 4.3 below.

4 Examining the wider industry benefits

When assessing the potential of TSE it is necessary to look beyond LCOE and examine the wider offering. While the technology is currently more expensive than other forms of energy, as can be seen in Section 3, it has undeniable advantages that can complement other forms of energy.

4.1 Potential sites in the UK and France

As has been mentioned, there is multi-GW deployment potential in the UK and France. Most of these sites are close to shore (<5km) which reduces the cost and complexity of subsea cabling. It also reduces the environmental and heath and safety impact associated with subsea construction and operations.

A key advantage of TSE is the small footprint of devices, which enables high energy density compact farms. Recent research from the University of Manchester, funded through TIGER, suggests average power densities of tidal farms in the 35-50 MW/km^2 range [67]. This is much higher than the 4-7 MW/km^2 seen on average for offshore wind farms [68] [69]. Being able to put devices closer together also reduces costs associated with array cables, installation and O&M (through lower vessel fuel usage and time at sea required).

4.1.1 UK

In the UK there is a good geographic spread of sites across all four constituent countries:

- Scotland has the largest TSE potential in the UK. The Pentland Firth, between the Scottish mainland and Orkney, has multi-GW potential. There are also numerous sites across the Western Isles, Orkney and Shetland. In these areas there are remote island communities who would benefit from smaller scale projects to reduce reliance on diesel.
- England has notable sites on the south coast close to population centres which could provide upwards of 500MW of capacity (PTEC, off the south coast of the Isle of Wight, and Portland Bill). There are also low flow sites in Cornwall, for example the Isle of Scilly and Cape Cornwall, and off the East of England.
- Wales has the Morlais site in the north. This site has an estimated 240MW capacity [70] and is where Magallanes Renovables secured a CfD in June 2022. Other sites around Wales include Bardsey Sound and Ramsey Sound which could produce tens of MW.
- Northern Ireland is home to Strangford Lough where developers such as Minesto, Gkinetic and QED Naval have tested. It was also where the first MW scale TSE turbine in the world was deployed: the MCT SeaGen turbine in 2008. The Crown Estate have

historically provided leases for other sites off the north coast (Torr Head and Fair Head, estimated 100MW each).

The Channel Island Crown Dependencies (Bailiwick of Guernsey and Bailiwick of Jersey) also have access to significant TSE resources. For example, studies have estimated the Alderney Race realistic generating capacity at 1.4GW (including French waters) [20].

4.1.2 France

The French side of the Alderney Race, the Raz Blanchard, has an estimated 2-3GW of capacity. A key advantage of this site is its key proximity to Cherbourg shipyard, which is being used for offshore wind activities, and the fact that it is close to population centres in Normandy. There is also proximity to the transmission network, with Flamanville nuclear power station located about 20km to the south of the Raz Blanchard.

Elsewhere in France, there are notable tidal flows in the Fromveur Passage (close to Ushant Island, where Sabella have tested), the Morbihan Gulf and Raz Barfleur [7].

4.2 Socioeconomic benefits and export potential

4.2.1 Rationale

A key benefit of any infrastructure project, large or small, is the socioeconomic value that it will inject back into the economy. Projects are desired that can invigorate both regional and domestic supply chains by creating value. This is typically measured in terms of gross value added (GVA) monetary value and full-time equivalent (FTE) jobs created.

The local content of projects is the proportion of project cost that is provided in geographic proximity to the project. This can be considered on a regional or national basis. Higher local content is desired so that the economic benefits of the project are retained by the local communities and government who approved the project.

The UK offshore wind industry has a target of 60% local content, as agreed between the government and industry in the 2019 Sector Deal [71]. The most recent estimate of local content for UK offshore wind projects is 48% [72], with the majority of this in O&M. Other high content areas include development phase activities, blade manufacture, installation and transmission infrastructure [73].

An additional benefit of high local content is reduced emissions associated with transporting components from overseas.

4.2.2 The tidal stream industry: local content and opportunities

To date, tidal stream projects have been delivered with very high domestic content:

- Nova Innovation delivered the first three turbines in their Shetland array with over 80% Scottish content. Of this, 25% of the project spend was in Shetland, providing direct local economic benefits. This demonstrates a key advantage of localised tidal projects.

- Orbital Marine Power delivered their O2 device in 2021 with 80% UK content [36]. This included Scottish steelwork, blades from the south of England and anchors from Wales.
- Hydroquest delivered their 1 MW Oceanquest device at Paimpol-Brehat using 80% French content. This will be replicated for their 17.5 MW FloWATT project in the Raz Blanchard.
- Normandie Hydroliennes (a JV including SIMEC Atlantis) analysed the French supply chain for their Raz Blanchard array and concluded that up to 100% of the turbine unit could be supplied by French companies.

Technology developers have reiterated their desire to keep domestic content high where possible, and similar levels of UK content are anticipated for the upcoming AR4 projects. There is even scope to improve on these impressive numbers further, for example Orbital Marine Power have previously indicated that 95% UK content could be possible for future projects [74].

The majority of non-UK content is in the powertrain, for example bearings, gearbox and generator. SKF, a Swedish company, are a key supplier of these components for several turbine manufacturers.

SMEIG, through discussions with the marine energy supply chain, identified several key areas which Scotland and the UK could capitalise on to keep domestic companies at the forefront of the supply chain [75]. These included:

- System integration
- Development of power electronics and control systems
- Creation of facilities to enable manufacture, quayside assembly, dry commissioning, device deployment and O&M.

Their recommendations were for the Scottish Government to create a “Centre of Excellence for Marine Renewables”. This would further develop indigenous capabilities and support upskilling of the workforce, to prevent supply chain bottlenecks from forming and stifling project deployments.

4.2.3 Benefits of a vibrant commercial industry

As the TSE industry is still at an early stage, socio-economic benefits have been modest and localised. The benefits of the next commercial generation of projects, namely the 40.8 MW awarded in UK AR4 and the French projects in the Raz Blanchard, are at too early a stage to be determined. This is because technology selection and procurement activity is ongoing.

GVA and FTE potential

ORE Catapult analysed the GVA and FTE-year jobs created by the 2021 Orbital O2 device manufacture, assembly and deployment. Orbital provided a breakdown of O2 costs, including non-recurring engineering costs. These were used to calculate GVA and FTE-jobs equivalent for each cost category by assigning Standard Industrial Classification (SIC) codes and cross referencing against input-output tables to determine appropriate calculation multipliers.

The GVA of the O2 device was calculated at £10.6M, with 40% of this direct GVA. The O2 device construction was estimated to have created 49 direct and 45 indirect FTE-years, for a total of 94 FTE-years.

The analysis was scaled up to consider a 20MW farm of O2 devices. Costs of subsequent units were decreased according to a 13% learning rate, consistent with previous studies [12]. Jobs were calculated at 46 FTE-years per MW (direct and indirect). This exceeded the approximate 15-25 FTEs per MW that has been estimated for wind and solar in other studies [76] [77] [78].

In 2022, as part of the ELEMENT project, INNOSEA examined the socioeconomic benefits of deploying 1MW of TSE in four countries: France, the UK, Italy and Norway [79]. They considered three scenarios: baseline content estimates, high content (100%, reflecting total European content) and low content (50%). They determined that such a project could generate between €13.7 – 27.4M of local GVA and support 47.4 – 94.8 FTE per MW in the construction phase. The baseline of 60.6 FTE/MW consisted of 36 direct and indirect FTEs, in alignment with the 46 FTEs estimated by the Catapult/Orbital study.

Long term forecast

The Policy and Innovation Group from the University of Edinburgh recently estimated that TSE could provide between £5Bn and £17Bn GVA to the UK economy by 2050 [10]. They examined "low" and "high" ambition scenarios and assumed that the capacity and LCOE targets from the EU SET ocean energy plan were met. In the high ambition case they estimated that the UK could retain 25% of international value generated by exporting goods and services worldwide, this accounting for three-quarters of the GVA. The study, utilising ESME modelling from the Energy Systems Catapult (ESC), assumed a conservative UK deployment of 6GW by 2050. This is far below the 10GW+ potential that the UK has [6], thus GVA could exceed this if build-out is more aggressive.

4.3 Energy system benefits

4.3.1 Energy system costs of variable renewables

Most renewables are variable and non-dispatchable, meaning that they are not inherently available on demand. While wind and solar costs can be cheaper than fossil fuels, the variable nature of these renewables means that they add cost to the overall energy system in several different ways. These include:

1. The cost of grid upgrades to transmit the power from where it is generated to the main population centres where it is needed (for example onshore wind from Scotland to England).
2. The cost of reserve capacity required to ensure that the peak demand can be covered at all times, for example during lulls in wind or solar resource.
3. The cost of short term, fast-switching flexible reserve to ensure grid voltage stabilisation, again in the case of lulls or excessive renewable energy resources.
4. The cost of curtailment, payments made to farm owners to limit power output when there is too much generation.

Balancing mechanisms are in place to ensure that energy supply can match the demand at real time without causing disruption to grid frequency. Forecasting errors of variable renewables often means that conventional fossil fuel generation needs to be brought online to meet demand and stabilise grid voltage. The cost associated with this has increased as the proportion of intermittent renewables on the system has increased.

As well as short term forecasting, longer term fluctuations in intermittent renewable resources can also be problematic for the wider energy system and has important implications for energy security. For instance, 2021 has had lower than average wind speeds in the UK. This meant that gas had to supply more generation, depleting reserves and further increasing already high gas prices. With such increasing gas usage also comes increased greenhouse gas emissions, which hinders UK efforts to meet its 2050 net zero targets.

One recent study that attempted to quantify the additional costs to the energy system was published by the UK Government Department for Business, Energy & Industrial Strategy (BEIS): *Electricity Costs 2020* [80]. This introduced the concept of enhanced

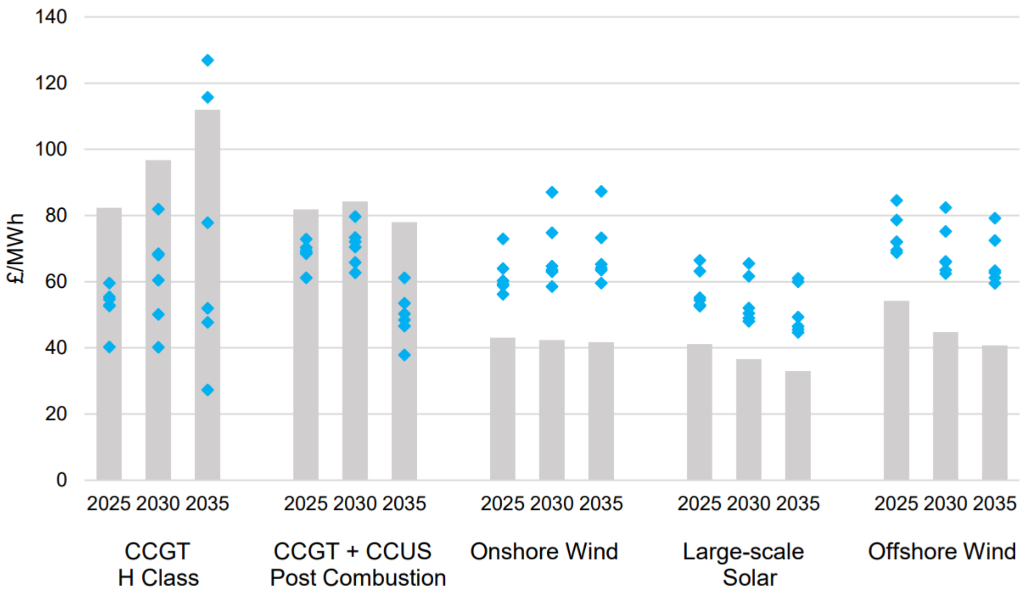


Figure 9 – Enhanced LCOE for five different technologies (blue diamonds), taken from the Electricity Generation Costs 2020 report [80].

LCOE, a metric combining conventional project costs with the costs incurred within the electricity system (factoring in the location of the generation, its timing and the balancing required). This applied methodology devised by Frontier Economics and published in their 2016 report: *Whole power system impacts of electricity generation technologies* [81].

When factoring in these additional system costs, BEIS estimated the LCOE of wind and large scale solar to be 20-100% higher than their baseline estimates in some scenarios, as shown in Figure 9 (the different scenarios represented by the blue diamonds).

4.3.2 Predictable, cyclical power

Tidal energy is generated by the relative movements between the Earth, Moon and Sun. This means that it is decoupled from other renewable resources and can also be forecasted hundreds of years into the future. This makes the power output firmer and more dependable, with consistent peaks in tidal flow each day.

Frontier Economics pointed out that tidal stream will not add to balancing costs, because the tides can be forecasted with “near certainty” [81]. They also note that, because there is no correlation between the tidal and wind resource, they complement each other well in providing smoother power output and diversification in the energy supply.

The current energy crisis has its origins in supply/demand mismatch from the COVID-19 pandemic which was exacerbated by a low wind year in 2021 (depleting European gas reserves) and the Russia-Ukraine conflict. Predictable energy from TSE would insulate consumers from volatile gas price rises by reducing the amount of dispatchable gas needed to balance the electricity system.

4.3.3 Tidal stream system benefits in a net-zero future

In late 2021 ORE Catapult led a TIGER-funded study to quantify the impacts of tidal stream on the electricity system. The aim was to gain insights on the following aspects:

- Can tidal stream reduce the costs of the wider electrical system?
- How much tidal capacity could be economically deployed, given the scale and costs of other renewables?
- What LCOE is needed to justify large scale deployment of tidal stream, from a system cost perspective?

Modelling of the energy system was outsourced to Imperial College London (ICL), who modelled different scenarios using their Integrated Whole Energy System (IWES) model. The key output from IWES is the net cost of the whole energy system in 2050. Further details on the IWES model and research methodology can be found in Appendix D.

The study examined the 2050 UK energy system assuming that the government’s net zero had been reached.

Key Findings

The simulation results offered deep insight into how tidal stream could impact the balance of the 2050 energy system. Across the analyses, the IWES modelling showed the following:

- At an LCOE of £50/MWh tidal stream could reduce system costs by £100M per annum. This rises to a saving of £600M per annum at an LCOE of £40/MWh.
- Tidal stream displaced both renewable energy technologies and natural gas CCGT (NG CCGT), as shown in Figure 10. In the base case, tidal stream was found to reduce NG CCGT capacity by 40%: from 8.1GW to 4.9GW. Typically, more than half of UK gas is imported [82], with recent prices extremely high due to geo-political events, and so a thriving domestic tidal industry could significantly contribute to improved energy security.
- At an LCOE of £40/MWh, the model recommended installing the maximum amount of tidal stream onto the system (modelled as 20GW). At £50/MWh the optimal system contained 3.1GW of tidal stream. The energy system compositions are shown in Figure 11. The latter LCOE is 42% above the 2050 LCOE assumed for offshore wind (£35/MWh), showing that a premium for tidal stream is warranted, vs installing additional wind, as it improves diversity in renewable outputs.
- The breakeven LCOE of tidal stream was found to be £49-55/MWh, depending on the capacity installed. Below this level, tidal stream offered direct cost benefits to the grid and will displace cheaper renewables (for example offshore wind and biomass with CCS).

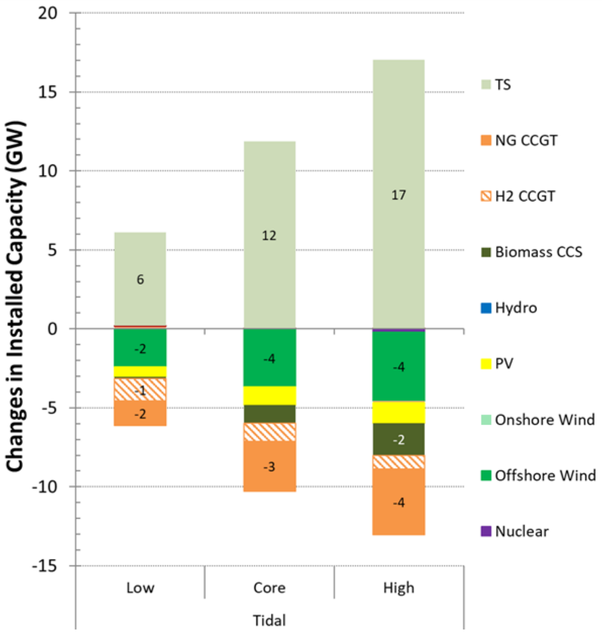


Figure 10 – The tidal stream added to the energy systems in the three capacity scenarios that were examined and the technologies that it displaced.

- The cost benefits were greater when the wind resource was lower, the technology becoming more cost competitive. Using the P5 wind scenario (instead of P50 in the base case) increased the tidal system cost saving to £800M per year, with a breakeven LCOE of about £72/MWh.
- The base case was considering the average power coefficient that has been demonstrated at the Meygen project [83]. This represents the efficiency of the turbine in converting the tidal flow to energy[11]. Increasing this by 20% (to represent future technology improvements) resulted in a £1.1Bn per annum system cost saving at a £40/MWh LCOE and a similar £100M per annum at £50/MWh LCOE.

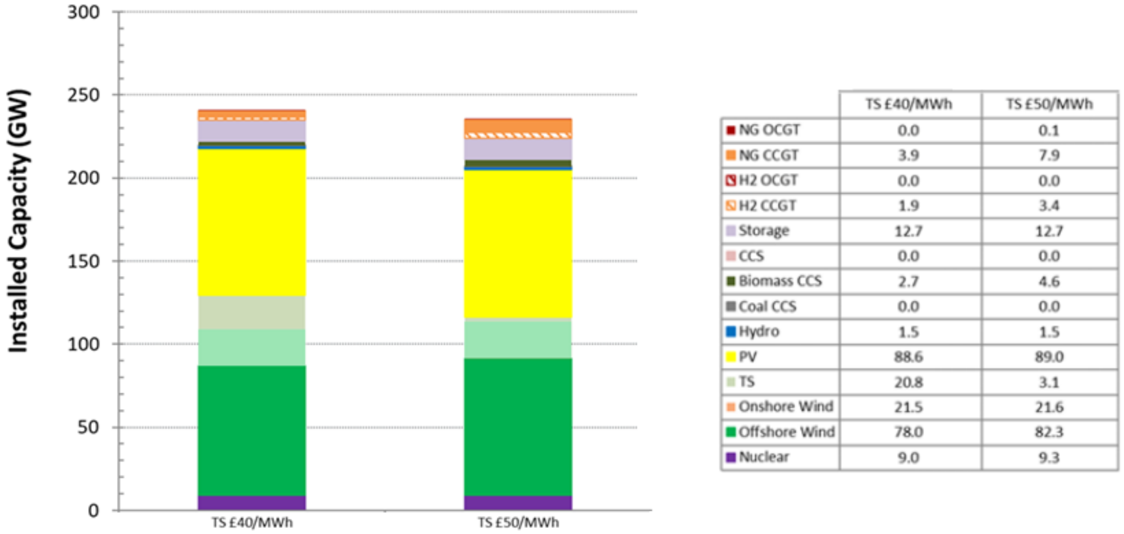
Arguably the main finding from this study is the £49-55/MWh breakeven tidal stream LCOE by 2050. While certain aspects of the tidal technology would warrant a cost premium (for example the high predictability), from a purely economic perspective this is the level that the tidal technology must reach to start to reduce the costs of the overall energy system. For a 10GW deployment, this LCOE level could be reached by 2050 with a learning rate in the range 10-15%.

4.3.4 Other system benefit studies

In recent years there have been other attempts to quantify the system benefits of TSE.

Innovation Needs Assessment: Cumulative benefits by 2050 (2019)

In 2019, BEIS commissioned the ESC to analyse the energy system benefit of tidal stream technology which was published as part of this 2019 report [12]. ESC used their Energy System Modelling Environment (ESME) model, a whole energy system model which simulates the UK electricity network.



	TS £40/MWh	TS £50/MWh
■ NG OCGT	0.0	0.1
■ NG CCGT	3.9	7.9
▨ H2 OCGT	0.0	0.0
▨ H2 CCGT	1.9	3.4
■ Storage	12.7	12.7
■ CCS	0.0	0.0
■ Biomass CCS	2.7	4.6
■ Coal CCS	0.0	0.0
■ Hydro	1.5	1.5
■ PV	88.6	89.0
■ TS	20.8	3.1
■ Onshore Wind	21.5	21.6
■ Offshore Wind	78.0	82.3
■ Nuclear	9.0	9.3

Figure 11 – Optimal power generation portfolio for tidal stream LCOE of £40/MWh and £50/MWh

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[11] "Water to wire", to the point that the power is exported to shore. An additional 4% in losses were added to account for availability and electrical losses.

[12] BEIS, *Energy innovation needs assessment: tidal stream* (2019)

In their “innovated” case they modelled capital costs reduction of 40% and capacity factor improvement from 30% to 39% gradually from 2020 to 2050.

Their results found that tidal stream could reduce system costs cumulatively by £1.8 billion by 2050. 16 GW of tidal capacity was installed by 2050, the majority of this being built between 2040 and 2050 as they assumed that lower cost renewables would be preferred in earlier years.

The low amount of cost reduction[13] combined with the fact that most of the deployment is after 2040 makes this study a conservative and pessimistic estimate.

EVOLVE project: Reducing dispatch cost (2022)

The Economic Value of Ocean Energy (EVOLVE) project is a €1M project investigating the economic value of including marine energy farms in European markets [84]. The project consortium, led by Aquatera, includes the University of Edinburgh, WavEC and Orbital Marine Power.

The project has included an analysis of the UK energy system using a temporal dispatch model that matches electricity supply and demand across the energy system. Initial results have indicated that, for 2030, 1GW of marine renewables (TSE and wave energy) could reduce the total market dispatch cost by 1%, equivalent to a £114M cost saving per annum in the energy system [85]. The 1GW of marine energy also led to a 3% reduction in carbon emissions with 300GWh less gas generation. Increasing the marine energy installed to 10GW increased the system cost saving to £860M. Note that these are gross cost benefits and do not consider the cost of revenue support for the marine renewable technologies.

The project is ongoing, with further studies planned that will investigate the net zero 2050 case as well as the Irish and Portuguese energy markets.

Aalborg University: TSE ability to displace other renewables (2022)

PhD research from Aalborg University, focussing on the Faroe Islands, found that TSE can displace more mature generation technologies [86]. Considering 100% renewable solutions, 72MW of TSE could reduce overall system capacity by 18% in 2030, including a reduction of 79MW of solar, 66MW of wind, 9MW of hydro and 1MW of battery storage. The reason is because of the predictable, cyclical nature of the resource and the fact that the main tidal sites in the Faroe Islands are out of phase, meaning that TSE can provide consistent power throughout the day.

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[13] For context our 2018 cost reduction report estimated £90/MWh after 1 GW installed, a reduction of 70%, compared to 40% reduction after 18 GW installed in the ESME BEIS study.

5 Conclusions

This study has assessed the cost reduction narrative surrounding TSE. This has included derivation of an updated LCOE reduction trajectory that can be used to monitor and evaluate the progress of the industry over the next 15+ years.

This chapter summarises the key conclusions and findings from the study and offers recommendations for policymakers and technology providers.

5.1 State of the industry

In Chapter 2 we summarised recent progress in the TSE industry, including commentary on the key technologies, international markets and turbine deployments since 2016.

Technologies

TSE is a vibrant, exciting technology. There are a large number of technology providers with different device scales, operating principles and target markets.

This variety in the industry is a good thing, as this will enable cost reduction through competition. It also means that there is more chance of developing cost optimised solutions by capitalising on a greater pool of ideas and different ways of thinking.

It is also clear that the industry has seen notable convergence: for example 2/3rds of the devices shown in Table 1 are horizontal axis turbines.

Different sites will be suited to certain device concepts. Shallower sites will benefit smaller rotor devices. As the industry matures and higher flow sites get developed the industry will pivot to low flows sites (<2m/s max spring tide) which will be particularly attractive for alternative technologies like kites.

Markets

The UK remains the most attractive global market with over 10GW potential, the presence of a large number of technology providers and research institutions and a budding supply chain The TSE ring fence in AR4 was an important endorsement of the industry and the 40.8MW of capacity at £178/MWh was a lower strike price than many had expected. The increasing emphasis on domestic energy security opens up a significant opportunity for TSE to build capacity as a reliable and fully forecastable complementary renewable energy source.

France is also a market of significant interest, with most of the potential in one area: the Raz Blanchard in Normandy. This is close to population centres and industry (for example Port of Cherbourg) and hence presents an exciting opportunity for low LCOE tidal farms. Two farms are being developed here, by Hydroquest and Normandie Hydroliennes, which could see 30MW installed in 2025/26.

The third leading global market is Canada, the only country in the world to have offered consistent revenue support to the TSE industry (via PPA at FORCE). 30MW has been allocated at FORCE and anticipated in coming years. Canada is also an increasingly interesting export market for UK based developers, for example Sustainable Marine and Nova Innovation.

Summary

In our opinion the TSE industry in the UK and France has never been stronger and there is a huge opportunity to capitalise on. Commercial opportunities can be augmented with cutting edge research, as evidenced by the scale and variety of projects described in Section 2.4.

5.2 The LCOE trajectory

LCOE trajectory

In Chapter 3 we presented our updated LCOE trajectory. Building on the previous ORE Catapult study from 2018, this included up-to-date data from technology suppliers and nine different scenarios to quantify uncertainty. Our estimates consider larger utility scale devices designed for the wholesale energy market.

- Currently the industry LCOE is £259±30/MWh (assuming the hypothetical case of small arrays of 3-5 devices installed in 2023).
- By 2026 we predict LCOE of £193±48/MWh
- By 2030 we predict LCOE of £116±38/MWh
- By 20235 we predict LCOE of £78±25/MWh.

These estimates assume that the industry is appropriately supported by policymakers through revenue support market mechanisms (CfD, FiT). By 2035 we assume that the UK will have installed 877MW[14] and France 783MW.

In terms of installed capacity in the UK and France, we estimated an LCOE of £98±32/MWh by 1GW installed. This aligns with the results of the previous ORE Catapult 2018 study.

Cost reduction mechanisms

In the shorter term (pre-2035) the most promising cost reduction mechanism is to scale up devices by increasing rotor diameter and rated power. While site specific, this could reduce LCOE by 40%. This applies to most device concepts, be they smaller or larger devices.

Other cost reduction drivers include economies of volume from larger farms (25-50% LCOE reduction), reduction in WACC (5% LCOE decrease per 100 basis point WACC decrease), move to piled foundations for fixed bottom devices (3.4%+ LCOE reduction) and piled anchors to floating devices (9.5% LCOE reduction).

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[14] In line with MEC target of 1GW of marine energy by 2035.

In the longer term (post 2035) cost reduction will be enabled by further reductions in WACC and improvements to economies of volume (including highly automated volume manufacturing). Innovative device concepts targeting low flow sites, run of river and ocean currents will unlock new sites and further cost reduction pathways.

5.3 The wider benefits

In Chapter 4 we examined the wider benefits of TSE technology, showcasing studies from both within and outside the TIGER project.

Societal benefits

- Across the UK and France, tidal sites are very close to shore and generally close to population centres (e.g. PTEC in the UK, Raz Blanchard in France). This reduces cost and environmental impacts of laying subsea cables and costly grid upgrades.
- Tidal farms can be deployed at much higher densities than other types of renewable energy (e.g. by a factor of 5-10 compared to offshore wind farms). This means equivalently sized farms will take up much less space, reducing issues with other sea users and making some elements of installation and operations more efficient.
- Tidal projects have been installed with very high domestic content, typically over 80% (e.g. Nova Innovation's Shetland Array and Orbital Marine Power's O2 at the Falls of Warness). This has significant benefits for local communities, creating jobs and creating GVA for both the local and national economy.
- Studies have estimated that TSE projects provide FTE equivalent jobs in the range of 35-45 per MW deployed. This exceeds the 15-25 FTEs that have been estimated for wind and solar in other studies.
- The University of Edinburgh recently estimated that TSE energy could provide £5-17Bn to the UK economy by 2050 under fairly pessimistic assumptions (6GW deployed by 2050). There is a significant export potential, with the UK capable of retaining 25% of international value generated through exports.

Energy system benefits

Unlike other renewables, TSE is completely predictable. This unique advantage gives it significant benefits for the wider energy system:

- Other renewables like wind and solar are intermittent and prone to weather forecasting errors. These increase energy system costs associated with balancing, curtailment and reserve capacity payments.
- BEIS in their report *Electricity Costs 2020* calculated that, if these costs were properly included, it would increase the LCOE of wind and solar by 20-100%.
- A TIGER funded study examined the 2050 net zero UK energy system, finding the following:

    - TSE could contribute £100-600M in cost savings to the UK energy network per annum, displacing both fossil fuels and other renewables.
    - TSE would displace gas CCGT, reducing the amount of gas required for UK generation by 40%. This would greatly increase domestic energy security.
    - In a low wind year (P5) the benefits of TSE increase to £800M per year.
    - The LCOE of tidal in the baseline was higher than offshore wind (£50 vs £35/MWh) and yet it was still chosen by the system. This shows that a premium for TSE energy is warranted as it improved diversity in renewable outputs.
- The EVOLVE project, led by Aquatera and with modelling from the University of Edinburgh, determined that 1GW of marine renewables (wave and TSE) would reduce energy system cost by £114M. This occurs by improving the diversity of energy supply, better matching the demand profile.

5.4 Summary and concluding remarks

This study has presented a third party, updated cost reduction trajectory for the industry. The LCOE trajectories will act as a blueprint to track the progress for the industry and allow policymakers, technology providers and other stakeholders to benchmark progress.

As well as this, the study has presented a summary of industry progress over recent years. TSE is an exciting domestic industry for both the UK and France, and both countries can kickstart TSE into a global phenomenon.

The complete predictability of the tidal resource makes TSE unique and gives it the ability to strengthen energy security, lowering energy bills by reducing costs associated with supply/demand mismatch.

6 Recommendations

6.1 Recommendations for policymakers

Commit to industry target

In the UK the AR4 ringfence has reinvigorated the TSE industry, bringing supply chain onboard and increasing private investment opportunities. Similar positive steps are being made in France, with encouraging discussions between project developers and the government.

While these are good first steps, what the market needs more than anything is long term commitment and certainty. The government has currently stated aims for offshore wind of 50GW by 2030 [87]. This, along with the Sector Deal from 2019, has given certainty to the offshore wind market and has made it more attractive to new developers and suppliers (for example oil and gas majors like TotalEnergies and BP).

The supply chain also needs sight of a clear project pipeline to enable investments in workforce and facilities and give time for projects to be delivered. This will improve project delivery efficiency and reduce project LCOE, allowing larger arrays to be deployed sooner.

We encourage policymakers to state long term deployment targets for the sector. We endorse the MEC's UK target of 1GW of ocean energy by 2035 and there is no reason TSE could not make up 850-950MW of this. We also endorse 750MW by 2035 as is envisioned by French industry.

While a simple action for policymakers, stating such goals will give the private sector confidence. This will encourage the flow of private capital and ensure that both the UK and France can become world leaders in this field and reap the economic benefits of exporting technology and expertise across the world.

Support via market mechanisms

An industry target will set the course for the industry but needs to be backed up by consistent revenue support. The TSE industry has proven to be incredibly resilient in the UK and France. Since 2016, when the industry lost access to revenue support in the UK, companies have soldiered on: deploying technology prototypes, reducing costs and improving performance. These successes have been achieved on very tight budgets.

Arrays of devices will unlock significant cost reduction through economies of volume and by spreading fixed project costs over a larger number of devices. Such projects, however, require upfront investment. The CfD mechanism in the UK has worked wonders for offshore wind, giving the private sector confidence in future cashflows and increasing their appetite to invest capital.

In the UK the best way to support the industry in this crucial early stage is to maintain a ringfenced amount in upcoming CfD rounds. It is important that TSE is given a provision, as it is an emerging technology and currently unable to compete with the scale of more established forms of renewable energy. The dependability and predictability of TSE is also something that is not currently valued in the CfD mechanism. Project owners are incentivised to generate whenever they can and are not exposed to the costs that intermittent renewables cause in the wider energy system.

Given the unique, predictable nature of tidal, we believe that it warrants ringfenced CfD support. This will enable the significant energy security benefits to be realised, as the industry will be able to scale up and drive down LCOE.

While early discussions in France have been focussed on PPAs for specific projects, which makes sense given the current industry scale, we believe that competitive auctions will help to drive down costs in the longer term after the first pilot arrays are installed.

Streamline approval processes

Currently in the UK there are 140MW of TSE projects in the pipeline with the necessary full consents (lease agreement, marine license and grid offer) [88]. Assuming future CfD rounds enable a similar capacity as AR4 (40.8MW) this gives 2-3 more auctions before new sites need to come online. The development timescale is long, for example it took over three years between the Meygen project securing a lease agreement from Crown Estate and getting a marine license from Marine Scotland [89].

The UK government have identified this as a priority for offshore wind, pledging to change planning legislation to cut offshore wind approval times from four years to one year [90]. This desire has been restated in the recent "Growth Plan" where the government aim to boost timelines of infrastructure projects in development, including offshore wind projects[15] [91]. The target is to enable the majority of projects in the pipeline to commence construction by the end of 2023.

This emphasis on speeding up development timescales is necessary for TSE too, to enable cost reduction through deploying technology at commercial scale. Due to the fluctuating support for the sector historically, project developers are hesitant to develop new sites as there are no guarantees that the long and costly process will lead to commercial opportunities in the future. Speeding up these timescales, as planned for offshore wind, will enable a strong and geographically diverse set of next generation projects to emerge.

In France, early discussions have focussed on a six-year timeframe between projects being awarded FiTs and commissioning. As for the UK, we also believe that these timeframes should eventually be shortened to allow more rapid deployments and unlock cost reduction and learning.

6.2 Further work

This study has raised several key areas that warrant further investigation:

Cost reduction monitoring framework

The LCOE trajectory forecast in this study has set a pathway for the sector to follow. To maintain credibility, it is important that this journey of LCOE reduction is appropriately monitored by an independent third party to make sure that progress is being made. ORE Catapult propose the idea of a "cost reduction monitoring framework" (CRMF) for TSE. This would take a similar approach to the offshore wind CRMF that was set up by the Offshore Wind Industry Council in 2014, which published regular LCOE estimates and industry milestones between 2014 and 2017 [92].

Within TIGER we have gathered cost, energy production and LCOE estimates from partners. These have been supplemented by ORE Catapult data and the wider

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[15] Offshore wind projects mentioned include remaining Round 3 projects, Round 4 projects, Scotwind projects, floating wind commercialisation projects and Celtic Sea projects.

literature. As new projects are installed, such as in the Raz Blanchard and upcoming AR4 projects, new data will emerge that will allow these metrics to be tracked over time.

The TSE CRMF would collect data from TSE project developers, anonymise this data and report key metrics and KPIs (for example weighted average WACC, LCOE estimates, CAPEX per MW etc.). This could then be plotted against our estimates in this report to see how the industry is performing and allow target areas for further work to be identified.

Building relationships

One of the greatest successes of the TIGER project has been the way that it has brought so many different organisations together. It has strengthened links between project developers and academia, crucial for reducing modelling uncertainties, de-risking and reducing LCOE.

It has also been very successful at building relationships between technology providers. These companies are in competition, but there are technological and regulatory issues common across the industry and working together has helped move the whole industry forward. One example of this is knowledge sharing between Hydroquest and Normandie Hydroliennes who are both developing projects in the Raz Blanchard.

TIGER will complete at the end of June 2023. Projects like the Raz Blanchard pilot farms and the site preparation at PTEC will carry on long after TIGER is over. It is crucial that we continue to build relationships across the industry, share knowledge, and maintain government confidence in the cost reduction trajectory of tidal stream supported by energy generation strategy so that the tidal market can establish. ORE Catapult is therefore convinced of the importance of a “TIGER2” project that focuses on innovative array scale technology and rolls out a robust cost reduction framework .

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Appendix A. The TIGER project

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

The project was launched in October 2019 and will be complete in June 2023. The project brings together a consortium of 18 organisations including tidal technology developers, research centres, project developers and academia. The project is led by the Offshore Renewable Energy Catapult (ORE Catapult).

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

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

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

The project aims to drive the growth of TSE by consenting 10+MW of new tidal capacity at sites in and around the Channel region, thus driving innovation and the development of new products and services. This will lead to:

- A reduction of greenhouse gas emissions (approximately 11,000 tonnes per annum).
- Investment in coastal communities, leading to an economic increase in GVA of €13m (~£11.1m) per annum.
- A tidal energy cost reduction towards the European Strategic Energy Technology (SET) Plan target of €150/MWh (~£128/MWh).

Figure A1 – The six tidal sites being supported within the TIGER project

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

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

Figure A1 shows the six tidal sites that are being supported through TIGER. These are located within or close to the Channel between the UK and France. A wide variety of potential site scales are covered: larger commercial sites (the Raz Blanchard, PTEC), mid-scale sites (Morbihan Gulf, Ramsey Sound) and smaller sites for testing and demonstration (Paimpol-Bréhat, Yarmouth Harbour).

Appendix B. Technology advantages/disadvantages

Table 4 shows the advantages and disadvantages of various technology aspects. Larger utility devices have been more commercially successful and generally demonstrate lower LCOE.

Table 4 – Advantages and disadvantages of different technology aspects.

Technology aspect	Type	Advantages	Disadvantages
Device scale	Micro/Small scale (<1MW)	Quicker to deploy and test Cheaper (on absolute basis) Can use smaller local vessels	Lower energy production Higher LCOE
	Utility scale	Higher energy production Lower LCOE Less devices for given farm size, reducing logistical challenges	Larger, more expensive vessels may be required Typically longer and more complex manufacture
Foundation type	Fixed	Synergies with established offshore wind foundations/best practice Smaller device footprint (higher array densities) Zero/low visual impact (underwater)	Device more difficult to access Larger vessels required with cranage (e.g. jack-up/DP vessel for utility scale) More expensive installation and O&M
	Floating	Device easier to access Quicker and cheaper O&M (smaller vessels) Higher flow speeds in water column (better resource)	Typically higher CAPEX per device More susceptible to wave loading Higher device footprint (lower array densities) Greater obstruction to other sea users
Power take-off	Horizontal axis	Synergies with wind turbine Higher energy production/capacity factors (higher tip speed) Better suited for high energy sites	Needs blade pitch/yaw to fully maximise production Research indicates wake effects more significant [67]z
	Vertical axis	Omni-directional – no need to pitch or yaw (improved reliability)	More complex design Higher CAPEX

		Research indicates reduced wake effects, higher array densities possible [67] Particularly suited for low-medium flow speeds [67]	
	Kite	Device movement through flow improves energy yield, particularly for low flow sites	Complex power take-off and control

Appendix C. LCOE trajectory methodology

Technologies

We initially considered six different, best in class TSE turbine technologies, as shown in Table 5. These represent the different scales and operating principles that are currently being developed across the industry.

Table 5 – The six turbines that were initially considered for the LCOE analysis.

Device		1	2	3	4	5	6
Foundation	Fixed	▨		▨	▨	▨	▨
	Floating		▨		░		
Rated power in 2022 (MW)	>3						
	2 - 3	▨	▨	▨			
	0.5 - 1				▨		
	<0.5					▨	▨
Power take-off	HATT	▨	▨		▨	▨	▨
	VATT			▨			
	Kite						
Initial farm size in 2022 (MW)	>10			▨			
	5-10	▨	▨				
	1-5				▨	▨	
	<1					▨	▨

Leading TSE technology developers provided us with cost and yield estimates for their technologies, which were used to derive LCOE using a Microsoft Excel based model. For the starting point we considered the hypothetical case of small arrays being installed in 2023, to provide a "present day baseline". The analysis was conducted in £2022 real terms.

Market forecasts

We derived LCOE trajectories for each technology by first considering anticipated buildout in different markets (UK, France, Canada, rest of world). The buildout was estimated pragmatically, considering industry ambitions and market sentiment. Our estimates are shown in Table 6.

Table 6 – Market projections assumed for the baseline TSE industry trajectory.

Region	Cumulative Installed capacity (MW)		
	2026	2030	2035
UK	42	262	877
France	33	157	783
Canada	30	230	680
Rest of World	13	80	241

Total	**118**	**755**	**2281**

The UK estimate reflects the MEC’s ambitions of 1GW of marine energy (TSE and wave energy) by 2035 and has been derived by considering potential capacity available in future annual CfD rounds.

The French and Canadian estimates both include known projects up to 2026 . Beyond 2026, the French estimate reflects the current ask of French industry to the government. Discussions are positive and ongoing.

The Canadian outlook is made up of increasingly larger projects every other year, the final capacity is comparable to the UK and French markets and represents the support of Nova Scotia and the Canadian Government to date.

The rest of world is a high-level estimate, devised by considering the sentiment of TSE developers to other markets.

These estimates are conservative compared to some industry outlooks. Most notably, as previously mentioned, the EU SET Plan targets 100 MW by 2025 and 1GW by 2030 across EU member states [11]. The origins of the 1GW SET plan target are from 2020, some two years ago, and there have not been commercial deployments in this timescale. The target also includes other technologies like wave energy. Given these facts we decided to opt for more conservative baseline forecasts to avoid “over-promising and under-delivering” which has historically been a problem for the marine energy sector.

Learning rates and LCOE

The market forecasts were combined with learning rates for each technology. We applied learning rates of 13–17% across most cost categories, consistent with the literature (e.g. [6]).

WACC and project lifetime were informed by discussions with TSE technology providers. WACC initially ranged from 7.5–9% (technology and scenario specific) and fell to 5–6% by 2035. This was modelled by applying a learning rate of 5% across the board. We set project lifetimes to 20 or 25 years, again technology specific and informed by discussions with project developers. This assumption was kept fixed across the dates examined.

The final LCOEs were calculated. These were cross checked against partner organisation’s LCOE estimates to ensure that the numbers were representative and fair.

From these initial trajectories we refocussed on “utility scale” devices (devices 1-3 in Table 5). This was because the three smaller devices are primarily focussed on localised, niche applications and were therefore found to be suboptimal from a wholesale market perspective (typically a 50%+ premium on LCOE). This allows the optimal large scale commercial offering from the sector to be isolated.

Sensitivities

To account for uncertainties in the data and differences in potential deployment locations we also modelled optimistic and pessimistic cost scenarios. These included adjustments to device costs, WACC, gross capacity factor and learning rates. These were technology specific and determined pragmatically according to the quality of data from the TSE technology developers. We derived nine trajectories in total (x3 device x3 cost scenarios). We consider the mean of the nine scenarios to be an industry representative LCOE trajectory, with uncertainty indicated by the standard deviation across all the scenarios.

We also examined sensitivities to the market forecast, namely the installed capacity. We considered optimistic and pessimistic projections, pragmatically estimated for the different geographies reflecting the sentiment and ambitions in the TSE industry. These projections are shown in Table 7.

Table 7 – Baseline, optimistic and pessimistic market assumptions examined.

Region	2030			2035		
	Optimistic	Baseline	Pessimistic	Optimistic	Baseline	Pessimistic
UK	372	262	127	1294	876	373
France	220	158	80	1158	783	330
Canada	330	230	107	1005	680	287
Rest of World	114	80	39	355	241	103
Total	**1036**	**730**	**352**	**3811**	**2580**	**1092**

Appendix D. Energy system benefit study details

The IWES model

IWES is a least-cost optimisation model. It can simultaneously minimise long-term investment and short-term operating costs across multi-energy systems (electricity, heating, hydrogen) from the supply side. It models the full energy network, to the end-customers, while meeting the required carbon targets and system security constraints. The IWES model has been used for several key pieces of work, including studies to advise the UK government on energy policy and strategy. For example, in 2018 ICL used the model to advise the Committee on Climate Change (CCC) on heat decarbonisation pathways, which was used as evidence to support the CCC's 2018 progress report to Parliament [93].

The key output from IWES is the net cost of the whole energy system in 2050. Countless model sensitivities can be probed to see how this overall cost is affected, and the entire system can be optimised for the lowest system cost, given technology specific costs and performance characteristics.

Research method

We used the UK as a case study, assuming a net zero energy system by 2050.

For the IWES model, ICL needed the locations and power output profiles of the tidal farms assumed for 2050. This data was supplied by University of Plymouth, a TIGER partner, and the University of Edinburgh, who have various models of the tidal current resource covering the UK. The locations and capacities were selected according to the Carbon Trust study *UK Tidal Current Resource and Economics Study* [94]. This provides locations and annual production estimates for about 30 sites across the UK, subject to environmental constraints. The University of Plymouth generated power time-series for farms at each site by quantifying the power capacity of each site and assuming a capacity factor of 40%. They checked the installed capacities in the Carbon Trust study against more recent estimates, updating where appropriate. This resulted in a baseline installed capacity of 11.8GW.

ICL built a model of the UK energy network by integrating this data into their existing model. They ran a number of sensitivities including:

- Varying the tidal stream installed capacity on the system.
- Varying the tidal stream LCOE.
- Varying the wind resource (P5 and P95) to see how this changed the benefit from tidal stream.
- Varying the tidal turbine power coefficient, to examine the impact of future technology improvements.

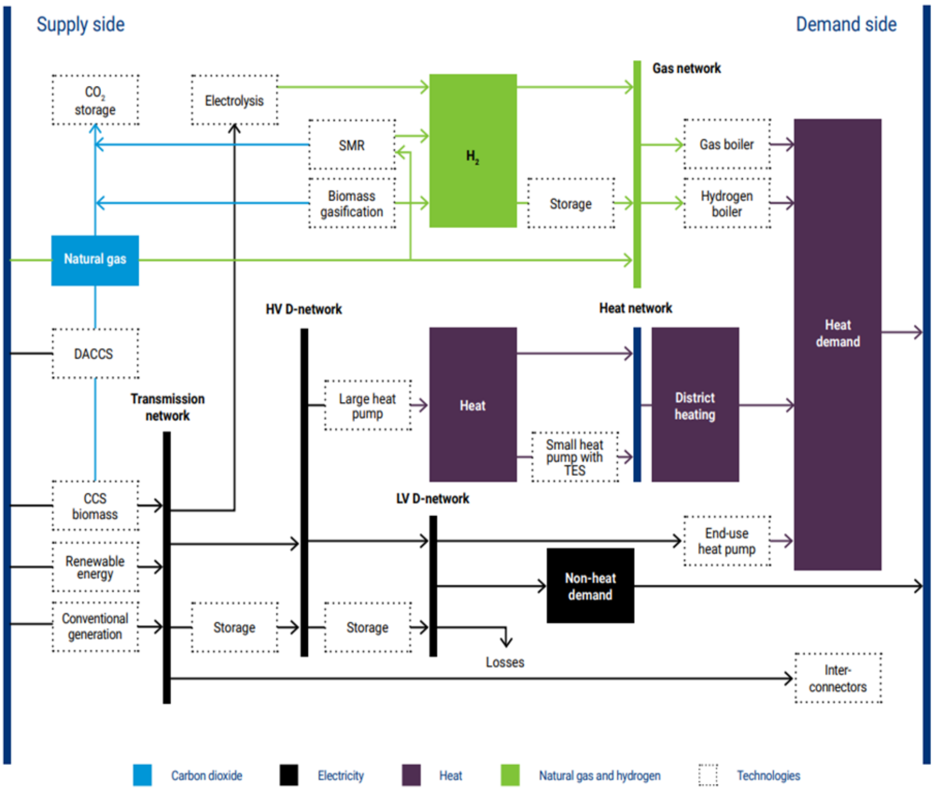

Figure A2 – The Integrated Whole Energy System (IWES) Model.