Review of Technical Assumptions and Generation Costs

Levelised Cost of Electricity from Tidal Stream Energy

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Abbreviations

ASP	Administrative strike price
BoP	Balance of Plant
CAPEX	Capital expenditure
CfD	Contract for Difference
DECEX	Decommissioning Expenditure
DESNZ	Department for Energy Security and Net Zero
DEVEX	Development Expenditure
EIA	Environmental Impact Assessment
FEED	Front End Engineering Design
FID	Final investment decision
FOAK	First of a Kind
INTOG	Innovation and Targeted Oil & Gas
LCOE	Levelised Cost of Energy
LR	Learning Rate
MWh	Megawatt-hour
NOAK	Nth of a Kind
NPV	Net Present Value
O&M	Operations & Maintenance
OPEX	Operational expenditure
PM	Project Management
TRL	Technology readiness level
TSE	Tidal Stream Energy

1 Introduction

The last decade has seen a major change in the energy landscape in the UK. Driven by the need to decarbonise and shaped by consideration of supply security and consumer affordability, our national generation portfolio has diversified to comprise a mix of traditional and renewable technologies at various stages in their lifecycles. This diversity in generation method provides us with a vital mix in supply profiles across baseload, variable and peak lopping, alongside fluctuating energy imports and exports through interconnection. Looking to the future, the UK Government's 'Net Zero Strategy' (HM Government [2], 2022) is recognised as fundamental to energy security, and could lead to 95% of British electricity being low carbon by 2030.

As a renewable but predictable resource, in which the UK is rich, Tidal Stream Energy (TSE) could provide an important contribution to the UK's net zero goal.

1.1 Project Overview

Frazer-Nash Consultancy Ltd have been asked by the Department for Energy Security & Net Zero (DESNZ) to review the levelised cost of electricity (LCOE) for Tidal Stream Energy (TSE). The data will be used as one of a series of inputs to the various models DESNZ use in their energy sector work, such as power sector optimisation and administrative strike price (ASP) calculations. The review provides an updated forecast of the LCOE for TSE between now and 2050, taking in to account recent progress in the industry and looking ahead to its future development.

The Levelised Cost of Electricity (LCOE) is the discounted lifetime cost of building and operating a generation asset, expressed as a cost per unit of electricity generated (£/MWh). It covers all relevant costs faced by the generator, including pre-development, capital, operating, fuel, and financing costs. This is sometimes called a life-cycle cost, which emphasises the "cradle to grave" aspect of the definition.

The levelised cost of a generation technology is the ratio of the total costs of a generic plant to the total amount of electricity expected to be generated over the plant's lifetime. Both are expressed in net present value terms. This means that future costs and outputs are discounted, when compared to costs and outputs today.

This analysis is Frazer-Nash's independent view but informed by the views of the industry and reviews of publicly available literature. Where sources are not provided it should be assumed that the statements are provided on the basis of Frazer-Nash's experience in the industry.

1.2 Exclusions

The following aspects are out of the scope of this study:

1. Consideration of costs and technical assumptions as an input to Enhanced LCOE calculations, which capture wider system impacts of individual generation units. This includes impacts on the wholesale market, capacity market, balancing and ancillary service markets, and networks (Department for Business, Energy & Industrial Strategy, 2020).
2. A review of the methodology that DESNZ use to calculate the LCOE. The methodology applied is consistent with the DESNZ approach outlined in (Department for Business, Energy & Industrial Strategy, 2020).
3. A comparison with the LCOE inputs and assumptions applicable to other generation technologies. As such, direct comparison of the LCOE estimates presented in this report with other technologies is not considered representative.
4. Evaluation of the cost of capital (hurdle rates) is out of the project scope. The hurdle rates used within the LCOE calculation are as provided by DESNZ.
5. Evaluation of the impacts of recent short-term macroeconomic effects (refer to Section 3.1.2 for further details).

6. Accounting for site-specific factors within the LCOE.

Additional assumptions made and limitations of the approach are noted in the report.

1.3 Structure of this Report

This report is structured in four main parts:

- Section 2 provides context for the report, including an overview of the current TSE landscape, a brief history of the industry's development, and an overview of TSE technology.
- Section 3 describes the methodology used for the study, including assumptions made and notable limitations.
- Section 4 describes the cost drivers of TSE, highlights opportunities for cost reduction in each area and a discussion of influencing factors.
- Section 5 describes the main findings of the study. It includes LCOE drivers and forecasts as well as highlighting opportunities for cost reduction in each area and a discussion of influencing factors.

In addition, Section 6 summarises our findings. This report is supported by a separate Excel spreadsheet which contains a breakdown of LCOE cost components in a format better suited to modelling. This template is in the format provided by DESNZ (BEIS, 2023).

2 Tidal Stream Energy Landscape

The viability of Net-Zero goals is highly dependent on the capacity of renewable energy generation, both in the UK and globally. This is outlined in the UK government's recent 'British Energy Security Strategy' (BESS) (HM Government [1], 2022) which strongly aligns to the wider 'Net Zero Strategy' (HM Government [2], 2022). Unlike other renewable energy technologies, such as wind and solar, tidal energy is not dependent on stochastic, meteorological conditions. TSE converts the movement of tides, which are driven by the motion of celestial bodies, into electricity. Tides are predictable many years in advance, so TSE offers a stable and predictable energy resource (ENTEC, 2007), (IRENA, 2020). TSE output is not correlated with wind and solar output, so combining all three generation types in the UK's energy portfolio will provide diversification and grid management benefits (Frontier Economics, 2016).

Additionally, TSE benefits from being cyclic - because almost all locations around the UK experience two high tides and two low tides a day, there are up to four TSE generation periods each and every day. There can be periods where there is maximum generation from other renewable technologies, such as wind and solar, followed by periods where meteorological conditions (such as low wind speeds or significant cloud cover) mean low or no generation. It has been shown that inclusion of TSE in generation mix may reduce the magnitude and cost of the energy storage solutions required to provide back-up capacity (Coles [1], et al., 2021).

There are two types of tidal technologies – range and stream. Tidal range technologies include barrages and lagoons; they harness the gravitational potential energy of the tides by generating electricity from the difference in water level between high and low tide. Tidal stream technologies harness the kinetic energy of flowing water, in a similar way that wind turbines extract energy from moving air.

Tidal range technologies face challenges of limited site availability, high capital cost and significant environmental impact (IRENA, 2020), and are out of scope of this report. Tidal stream technologies, in contrast, offer the potential for deployment at numerous sites and have seen growing interest from developers. They offer the potential for economies of scale and volume, which can be realised as designs are proven suitable for long term deployment in the marine environment. To date, there have been successful deployments of 2.0MW turbines, with further scale-up expected (IRENA, 2020).

2.1 Tidal Stream Technologies

Various turbine designs have been proposed for the extraction of TSE. These are summarised in Table 1 and Figure 1 (IRENA, 2020). Some designs incorporate more than one turbine in a single module structure.

Like wind energy, the most common TSE turbine design currently deployed is horizontal axis, with 13 installed globally as of 2020 (IRENA, 2020). However, full market convergence has not yet been seen as other designs are still entering the prototype and testing phase. (IRENA, 2020) discusses two installations of tidal kites and one installation of a vertical-axis turbine.

Within the horizontal axis TSE category, the modules may be held in place by either bottom-fixed or floating structures. The type of support structure chosen for a project is heavily influenced by numerous factors including the position of the module, the water depth, the sea-bed environment, and construction limitations.

Fixed structures can either use piling, where columns are sunk into the seabed; or gravity-based foundations, which rely on the weight of large amounts of concrete and steel to hold the modules in place. Gravity-based foundations are currently in use in the UK's largest tidal stream arrays: four 1.5MW turbines in Simec Atlantis Energy's MeyGen array and six 100kW turbines in Nova Innovation's Shetland array. They offer ease of installation as seabed drilling is not required and allow for adjustment post-installation to optimise the array. Developers of bottom-fixed turbines are likely to transition to monopile foundations, which are commonly used in offshore wind, provide greater flexibility to optimise the micro-siting of turbines due to a much smaller footprint than gravity-based foundations, and are less expensive due to reducing the steel requirement of the foundations by up to 90% (Coles, 2019). Bottom-fixed devices typically sit low enough in the water column to allow vessels to pass overhead, with minimum clearance requirements of 8m imposed, so they do not impact on local shipping activities. Bottom-fixed devices benefit from relative simplicity of design, learnings taken from the offshore wind industry and a smaller ratio of supporting infrastructure to rotor size i.e. lower material costs per MW.

Floating structures use anchors and flexible or rigid moorings to attach the structure to the seabed (ENTEC, 2007) (IRENA, 2014). Some of these designs hold the turbines in place on arms that can be levered up or down to allow easy access for maintenance of the turbines. Floating TSE devices can be towed to site for low-cost installation, flexible repositioning, and decommissioning. Floating platforms may also use a turret configuration to allow the device to passively align the turbines with the flow, without the need for a manual yawing system.

In both fixed and floating TSE, the scale of the devices varies substantially between projects. Fixed devices in the UK vary in scale from the 8m diameter 100kW Nova Innovation devices to the 18m diameter 1.5MW MeyGen devices, with industry plans to increase both the diameter and rated power further, following the trends seen in the wind industry (Coles & Walsh, 2019). Floating devices under development in the UK and abroad show even greater variability in scale, from 4m diameter 70kW turbines on Sustainable Marine’s PLAT-I device, to 20m diameter 1MW turbines on Orbital Marine Power’s O2 device.

Many floating TSE devices are multi-rotor, with the latest designs having between 2 and 6 turbines mounted on each module. There is currently more variability in overall device design between floating TSE projects and more convergence in design in bottom-fixed TSE projects, which therefore currently have a higher Technology Readiness Level (TRL). (An explanation of TRL is contained in Appendix A1.) However, the prevalence of floating TSE has increased notably in recent years, with three of the four TSE projects that successfully secured Contracts for Difference (CfDs) in Allocation Round 4 being floating. In that CfD round, the single fixed project had a far higher capacity (28MW of the total 40.8MW capacity awarded). Floating projects are typically at the demonstrator stage, with only one or two devices per project, whereas bottom-fixed projects are beginning to move to the FOAK stage, operating at small array scale.

The cost and performance of TSE schemes is based on the scheme location (which determines the TSE resource availability and distance to construction and O&M facilities) and technical factors such as the support structure, turbine design and electrical connections. At present, substations are located onshore and connected to turbines via inter-array cabling. However, it is expected that future deployments will shift to subsea hubs for efficient electricity export to shore and decreased cabling expense (Goss, 2021) (Noonan, 2019).

Generally, due to conservation of mass, shallower waters have faster flows and therefore are more suitable for economic extraction of TSE through horizontal axis turbines. Tidal kite developers, such as Minesto, seek to exploit the tidal energy resource in deeper waters with lower flow velocities, through operating their devices on a figure-of-eight trajectory, which creates higher relative flow speeds. These devices may expand the number of suitable locations for TSE extraction greatly. However, they are at a lower TRL than both types of horizontal axis turbines, so accurate information on costs is limited.

Table 1: Summary of Turbine Designs & Estimated Technology Readiness Level (TRL) (IRENA, 2020)

Turbine Design	Description	Estimated TRL
Horizontal Axis - Fixed	Similar to standard wind turbines, blades are fixed radially to a horizontal shaft. The turbine is attached to a module which rests on the seabed. Tidal flow causes the blades to rotate If the tidal flow is reversed, the turbine must be turned by 180° to continue generating.	8
Horizontal Axis - Floating	Turbines are of a similar design to fixed horizontal axis, but the module to which they are attached floats on the sea surface. The module is attached to the seabed with moorings and anchors. It is common for the turbines to be held on arms that can be levered up and down to allow easy access for maintenance. May use a turret configuration to passively align the turbines with the tidal flow, dispensing with the need for a manual yawing system.	7
Vertical Axis	The blades are vertical and parallel to the rotating shaft. Tidal flow through the blades causes the shaft to rotate irrespective of the flow direction.	5
Tidal Kite	A hydrodynamic wing (‘kite’) with an integral turbine is attached to the seabed or a floating platform via a cable. Tidal currents cause the kite to loop through the water in a figure of eight motion, increasing the speed of the flow through the turbine.	6
Venturi/Open-centre	The turbine is contained in a duct, which concentrates the tidal flow, causing an increased velocity when it reaches the turbine.	7
Reciprocating Device/Oscillating Hydrofoil	A hydrofoil attached to an arm is moved up and down by tidal flows. Electricity is generated by this movement being transferred to a turbine.	5
Archimedes Screw/Spiral	A helical structure attached to a generator rotates as tidal flows pass through it.	6

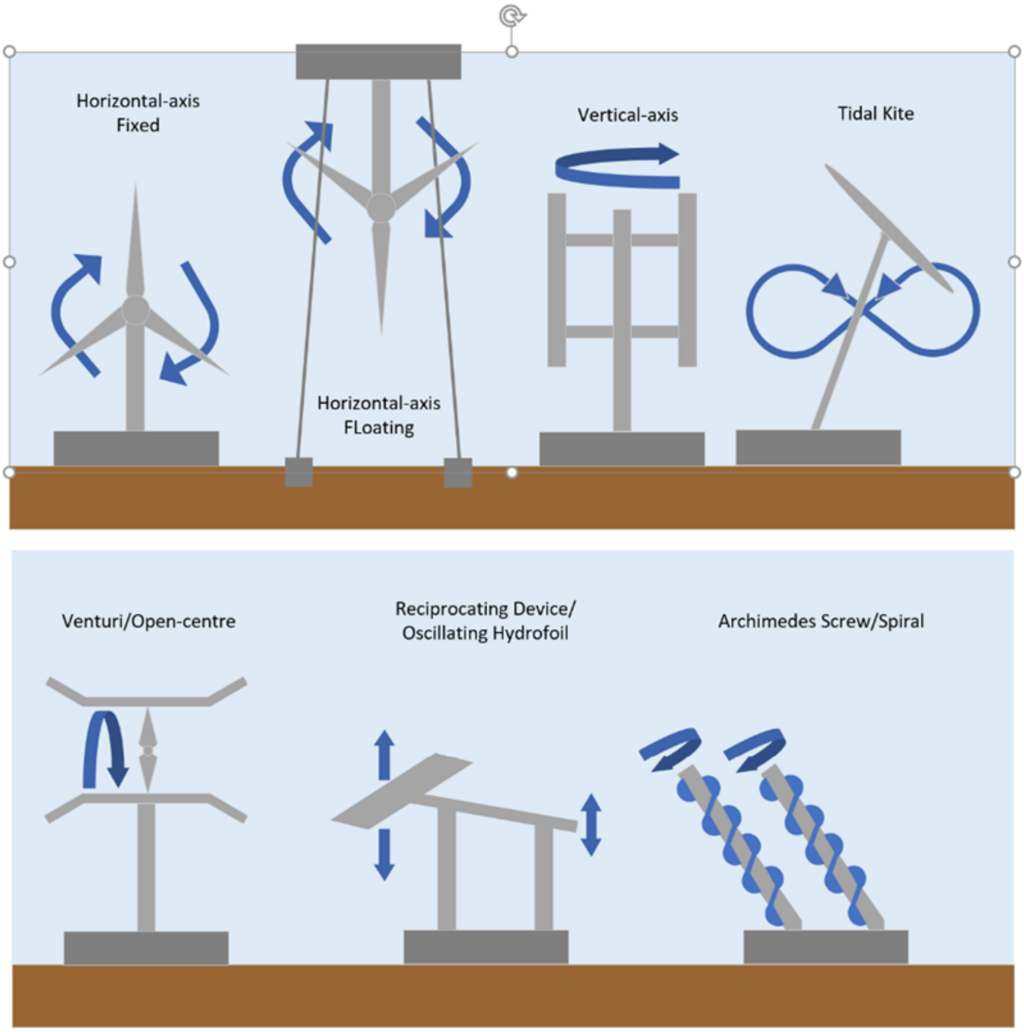

Figure 1: Tidal Stream Turbine Designs

2.2 Development of Tidal Stream Energy

TSE technology is still mainly in its prototype and testing phase, resulting in high investment costs and uncertainty. However, a shift towards commercialisation is evident, particularly in Europe, with 30.2MW being installed since 2010 (Ocean Energy Europe, 2023).

With optimum water depths and flow velocities, the UK holds a strong position at the forefront of this development. Nova Innovation deployed the world's first offshore tidal stream array in the UK in 2016. This has since grown in capacity from 300 kW to 600 kW, and now has a total of 6 turbines (Marine Scotland, n.d.). Since then, further successful installations have been seen with SAE's MeyGen installation of four 1.5 MW turbines also in 2016, planned to increase by 28 MW by 2027 due to a successful bid for a Contract for Difference (CfD) in 2021 Allocation Round (AR) 4 (SAE, 2023). Similarly, Orbital Marine Power have successfully installed a 2 MW floating device off Westray in Orkney consisting of 2 turbines with rotor diameters of 20m, and have plans to increase capacity with the addition of 3 more turbines (Orbital Marine Power, 2023), also supported by CfDs from AR4. Recent announcements suggest there is an ambition to install up to 12 Orbital devices at the Westray site, providing a total installed capacity of up to 30MW.

More recent deployments have been smaller. 2022 saw 3 low-capacity installations installed throughout France and Northern Ireland ranging from 12 – 30 kW (Ocean Energy Europe, 2023) with the aim of targeting isolated communities. Such targeted devices reduce investment risks of high-volume farms. 2023 is however expected to see an increase in deployments globally, with Canada having plans for demonstration projects totalling around 32 MW and China similarly likely to complete its demonstration project with the addition of a 1 MW turbine. (Ocean Energy Europe, 2023).

3 Methodology

To model the LCOE of TSE, the approach outlined in Figure 2 was taken. This approach was developed based upon previous expertise obtaining, combining, modelling, analysing, and presenting industry data.

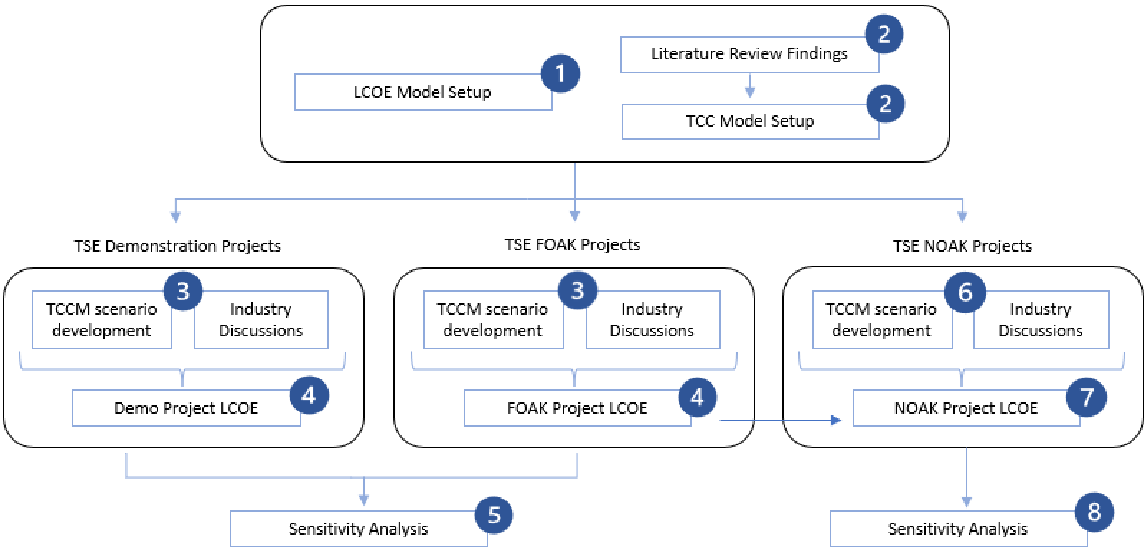

Figure 2: Modelling Approach to Generate LCOEs for TSE

Step 1, the development of a model to compute LCOEs using input cost data, is described in more detail in Annex A.1.

Step 2 covers the development of an additional model – the TSE Component Cost Model (TCCM) - to generate component costs for a range of example TSE projects. This was needed because, due to the early stage of development of the TSE industry and the limited number of existing projects, there was an understandable reluctance on the part of developers to share sensitive information. Regardless of this, the number of input data points from existing projects would also be insufficient for the LCOE model. The TCCM is described in further detail in Section A.2.1.3. and is a significant and valuable addition to the forecasting and modelling toolkit available for TSE.

Step 3 covers the iterative process followed to generate suitable input data for the LCOE model. This is described in more detail in Section 5. These data were then processed by the LCOE model at Step 4 to generate a distribution of LCOEs for Demo and FOAK projects.

At Step 5, a sensitivity analysis was conducted on key variables to understand their impact on the LCOE using the Demo and FOAK LCOE results as the baseline. This is detailed in Section 5.3.1.

Steps 6 and 7 are similar to Steps 3 and 4, but look at scenarios for longer term NOAK projects. Using the FOAK LCOEs developed at Step 4 as a baseline, projected LCOEs for a range of NOAK options were generated. This is detailed in Section 5.4. The sensitivity of NOAK values to different variables is also described in Section 5.4.

3.1 Assumptions & Limitations

The outlined approach is reliant on several assumptions. These, and associated limitations, are discussed in this section.

3.1.1 Assumptions

As specified by DESNZ, a constant hurdle rate of 9.4% was applied across each of the simulations modelled.

Cost figures provided have been aligned to 2020 prices in GBP. To achieve this, where appropriate, Frazer-Nash have inflated or deflated to 2020 costs using GDP deflators at market prices as provided by HM Treasury (HM Treasury, 2023). Where is it unclear from the source which year costs refer to, the year of publication has been used.

The calculations assume current government policies, and the principle of running regular Contract for Difference (CfD) support auctions, are unchanged throughout the analysis period. In addition, due to timescales, any announcements made within the 2023 March budget have not been considered.

Potential policy changes which could affect the LCOE of TSE include:

- changes to energy market strategy or policies, including those affecting:
    - access to seabed (and the rate of access), and the structure of seabed leasing auctions and option fees
    - consenting and planning
    - securing or paying for grid connections
    - support regimes (CfD auctions)
    - local supply chain content requirements
    - Offshore Transmission Owner (OFTO) regulations

- changes to fiscal, trade or foreign policy (within or outside of the UK)

A more detailed discussion on the various cost drivers of TSE can be found in Section 4.

3.1.2 Limitations

3.1.2.1 General

The LCOE model is only as accurate as the input data. Given the limited number of data points, a uniform distribution was selected to capture uncertainty in cost data. This distribution may not be reflective of the actual uncertainty in cost data. The model is adaptable to other distributions but there was limited information to justify their use. As the output distribution for LCOE is calculated using the input data distributions, the uncertainty presented in the output calculations of LCOE may not be reflective of the actual uncertainty in the data.

To some extent, the effects of this are illustrated through the sensitivity analysis (See Section 5.3.1) which models a wider distribution for different variables.

Due to a lack of data points from industry for tidal stream projects, the input data to the LCOE model has been generated using the TSE Component Cost Model (TCCM) described in Section A.2.1.3. The TCCM has been produced with reference to literature and with the input of technology vendors. However, the TCCM can only provide an estimation of the cost of tidal projects dependent on the project variables. The model cannot be further verified until the industry develops, and more cost data becomes available, but until then provides an order of magnitude cost approximation guided by industry.

3.1.2.2 Short-term Macroeconomic Uncertainty

Costs are provided on a 2020 basis and have been inflated or deflated to align with this year. There have been significant macroeconomic changes between 2020 and present, predominantly driven by the COVID-19 pandemic and Russia's invasion of Ukraine. These macroeconomic changes will impact costs differently and the full extent of these short-term effects is unknown, although there are signs of notable impacts on major capital projects both within the TSE industry and more broadly (for example recent reports concerning cost increases to renewable energy projects (Bloomberg, 2022) (IEA, 2021)).

For these reasons, the regression of recent costs to 2020 prices is subject to increased uncertainty. In our analysis we have included a comparison between 2020-base costs (as produced from the TCCM) and 2023-base costs (produced from a review of the TCCM results with industry and updating to reflect current economic conditions). This is to some extent an additional sensitivity analysis demonstrating the variability of costs of a current project under different macroeconomic conditions.

3.1.2.3 Site Dependency

To optimise power generation, it is necessary for TSE arrays to have a site-dependent design. The tidal resource differs between sites. The seabed condition, water depth, distances to shore, ports and grid connections, and consenting and planning considerations are all site-specific. This site variability impacts on the design and cost, and these more granular effects are not within the scope of this study.

For the purposes of this study, sites have been categorised predominantly by their turbine power rating and installed capacity (number of turbines). Although there is some correlation between these factors and site conditions (i.e. more favourable sites are likely to be developed earlier), significant differences remain between sites within each categorisation (i.e. within Demo, FOAK or NOAK projects).

Site dependency is not unique to TSE, but these effects have a larger impact than for other forms of power generation. This is because the tidal resource is dependent on many factors including, but not limited to, coastal geometry; seabed characteristics; local bathymetry; and the amplitude, frequencies and phases of local tides (Perez-Ortiz, 2014). These site differences, and thus LCOE differences, are captured to an extent by the LCOE distributions, but care should be taken to avoid assuming a single cost for the technology irrespective of site.

3.1.2.4 Bias (including Optimism Bias)

Optimism bias is the documented tendency to underestimate costs and overestimate benefits for a project or programme during the planning stages. To better understand and quantify optimism bias, in 2002 HM Treasury commissioned Mott MacDonald to undertake a study to review the initial business case cost estimates and the outcomes of large public procurement projects in the UK over the previous 20 years. This study (Mott MacDonald, 2002) revealed high levels of optimism bias across all industries, project types and expenditure types. The output from this study was incorporated into the Treasury's Green Book guidance (HM Treasury, 2020) on how to account for optimism bias in capital costs and works duration when developing a business case.

Optimism bias estimates are not recommended to be added to a project's budget, as this might lead to overspending. A more suitable use for optimism bias adjustment values is to confirm that a business case remains robust if costs rise to this level. Another use is to check if risk and mitigations are appropriately considered. The best estimate, not risk adjusted budget plus upper bound optimism bias, should be greater than the p90 risk adjusted cost estimate. In addition to comparisons with Green Book Guidance, optimism bias can also be estimated by considering evidence of past similar projects.

There is insufficient publicly available evidence from the TSE industry, which is driven by the private sector, for Frazer-Nash to attempt to use historical data to inform of appropriate levels of optimism bias. An attempt could be made to adjust the data to account for optimism bias based on the Green Book. However, this is subject to uncertainties, including:

- It is unclear how applicable the Green Book is to these projects, which are delivered by the private sector and differ from the projects analysed by Mott MacDonald and which inform the Green Book.
- It is difficult to determine suitable values for the criteria set out in the Green Book due to having limited information.
- It is unclear whether developers have already applied their own, internal, optimism bias based on their experience of delivering similar projects. Methods for compensating for optimism bias are likely to vary significantly between developers and are linked to the effectiveness of project management controls as well as the competence of project teams.

Information from industry, which has been used to inform the analysis in this report, may be subject to other sources of bias which could include:

- A desire to artificially inflate the projected cost of TSE, or of their own projects. This could be done to help obscure the data confidentiality, influence government policy (e.g. increasing future budgets made available for subsidy allocation rounds), influence supply chain negotiations by emphasising cost pressures, or otherwise secure more support for the sector.
- A desire to artificially deflate the projected cost of TSE, or of their own projects. This could be done to help obscure the data confidentiality or to help influence public opinion my making TSE appear less expensive.
- A conservative approach to projecting project costs at the early stage of projects utilising novel technology (over-compensating for optimism bias).
- Incomplete knowledge and incorrect assumptions.

Each company who engaged with this project came across as frank and open and was viewed (in the absence of any indication otherwise) as a reliable source. In light of the conflicting considerations above, it was therefore decided that no attempt would be made to correct for bias.

4 Cost Drivers of TSE

4.1 Introduction

This section discusses the main cost drivers for TSE, which informed the setup and population of the TCCM.

Prior to discussing potential cost drivers, it is worth putting the potential goal of achieving the lowest LCOE in context. Low energy prices have significant societal benefits, perhaps best highlighted by the widespread impacts to families and the economy observed during the current "cost of living crisis" which in part results from the recent abnormally high energy prices. However, "levelling up" communities, achieving Net Zero, and ensuring security of supply are also clearly beneficial.

Requirements for local content tend to increase the LCOE, whilst contributing to levelling up the economy and supporting UK businesses. The rate of deployment of low-carbon generation, such as TSE, can also be adversely impacted by focussing too much on driving down LCOE: lower rates of deployment will most likely lead to reduced carbon emission savings and reduce energy security. A relentless focus on reducing LCOE also increases supply chain stresses (supply chain risks are also increasing as individual components and projects increase in size and cost) which may in-turn lead to reduced deployment rates of TSE. For these reasons, and others, a desire to achieve the lowest LCOE should therefore be a considered goal.

4.2 Main Cost Drivers

The literature review and supplier discussions have indicated that cost reductions may be achievable in via:

- Economies of scale, allowing reduced costs across the board for TSE components as the size of the turbines increases
- Economies of volume, increasing the size of arrays deployed and enabling components to be manufactured more efficiently using volume manufacturing processes
- Financing improvements – primarily reduction in hurdle rate, driven by increasing confidence in the technology and better understanding of the risks involved in TSE

These, and other factors, are discussed in the following sub-sections.

4.2.1 Turbine Scale (Rotor Diameter and Power Output)

Increasing a turbine's rotor diameter or rated power offers developers the ability to install fewer turbines while still meeting a given turbine array capacity. As a result, the costs incurred for turbine installation, maintenance, and decommissioning operations are reduced. Additionally, to produce the same array power output, the CAPEX uplift in increasing the size or capacity of the turbine is relatively small compared with the CAPEX of additional, smaller turbines.

For example, it has been estimated (Coles [3], et al., 2021) that economies of turbine scale could lead to a reduction in LCOE of between 17% and 23% due to the 29% uplift in anticipated yield when progressing from a 1.5MW turbine to a 2MW one, the range being dependent on how much the CAPEX increases for the 2MW device.

However, the size and power that tidal turbines can reach is capped due to depth constraints and the location of exploitable tidal resource. Based on this, feasible maxima for rotor diameters and power outputs are likely to be in the range of ~26m and ~3MW respectively. So, whilst wind power has successfully upscaled with larger and larger turbines, this is not possible for TSE beyond these points.

Foundation costs make up a significant proportion of the lifetime costs of an array, so some developers plan to use several rotors on the same supports to spread the foundation costs over a higher-rated power (Goss, 2021).

As turbine and module designs are tested and proven in the marine environment, increased standardisation is expected. This may apply to individual components as well as whole system designs. Note that each site will have particular constraints, the blade being the most site-specific aspect. The nacelle and anchoring are more standard.

Standardisation requires the industry to settle around a limited number of suitable designs, and/or use interchangeable or modularised components. This will allow mass-production rather than bespoke manufacturing and allow the development of a competitive supply chain.

There are varying levels of competition at varying scales. Lack of competition drives up prices at some scales. TSE depends on the location as to which scale of technology is most appropriate and therefore how much competition can be generated in the supply chain.

It should be noted that as the industry develops from FOAK to NOAK, turbine design is likely to change, with the focus moving more towards overall cost reduction. At the Demo and FOAK stages, a higher priority is given to (a) technical optimisation in order to develop the best designs, and (b) using conservative estimates of various parameters (e.g. the loads to which the structure will be subjected) in order to ensure a robust test installation. This inevitably leads to some over-engineering and, as a result, costs are not optimal. However, cost optimisation of suitable designs becomes vital to successfully progress to the NOAK stage.

4.2.2 Array Size

A larger array will produce more energy. However, for TSE there is not a completely linear relationship between installed array capacity and energy output because, as the number of turbines increases within an array, global blockage effects increase so the expected output per turbine will go down (Goss, 2021).

That said, there are LCOE reductions to be achieved by increasing size of arrays. The costs per unit of production will decrease and components will become standardised. Fixed costs, for example associated with vessel mobilisation and onshore substation integration, are spread over more devices. The LCOE reduction in going from 2-10MW to 20-200MW projects was estimated at 40% by Wood in their report for the EnFAIT projects (Wood, 2019). Research from the TIGER project estimated a 28% LCOE reduction when increasing farm size from 8MW to 100MW (TIGER, 2022).

4.2.3 Financing Costs

The cost of finance is generally represented within LCOE models using a hurdle rate (sometimes referred to as "discount rate"). As understanding of, and confidence in, the TSE industry improves the risks will decrease leading to reduced financing costs. This will reduce the cost of projects overall.

However, industry sources have indicated that financing costs may increase between Demo and FOAK projects. This is due to the increased risk involved in funding larger arrays when some aspects of the TSE technology or process are still considered relatively novel.

The cost of finance is also influenced by macroeconomic factors which are not TSE specific.

4.2.4 Grid Costs

From engagement with industry, there are concerns that two areas of the grid connection process could negatively impact the LCOE: uncertainty whilst securing a grid connection and costs during operations.

When securing a grid connection, delays and price uncertainty risk delaying investment decisions and causing subsequent cost increases elsewhere in the project.

Once operational, various annual charges are paid by generators to contribute to grid costs. Some grid costs are largely dependent on a project's output or running regime, and are relatively evenly allocated per MWh between different generators. Transmission Network Use of System (TNUoS) charges are dependent on the area of the country in which the project is connected (National Grid ESO, 2023) with the aim of financially incentivising connections in regions which have a shortage of supply compared to demand. As sites with favourable conditions for TSE cannot be moved, and the locations of favourable sites are generally situated near less populated areas of the UK, a lack of grid infrastructure investment could cause regional cost variations to increase significantly.

In areas with a high generation TNUoS tariff, grid costs can make up a large proportion of the total OPEX costs. This is relevant to the Pentland Firth and West Islay sites, which have a large tidal potential (Coles [3], et al., 2021). In other tariff zones, the generation TNUoS costs are negative. For example, the Somerset and Wessex region in 2020 had a wider generation tariff of -6.14 £/kW. Therefore, a tidal stream project at the Minehead site (Coles [3], et al., 2021) would benefit from reduced total OPEX costs as the generator would be paid for this element of grid costs rather than charged. This is illustrated in Figure 3. It should also be noted that grid costs can change from one year to another.

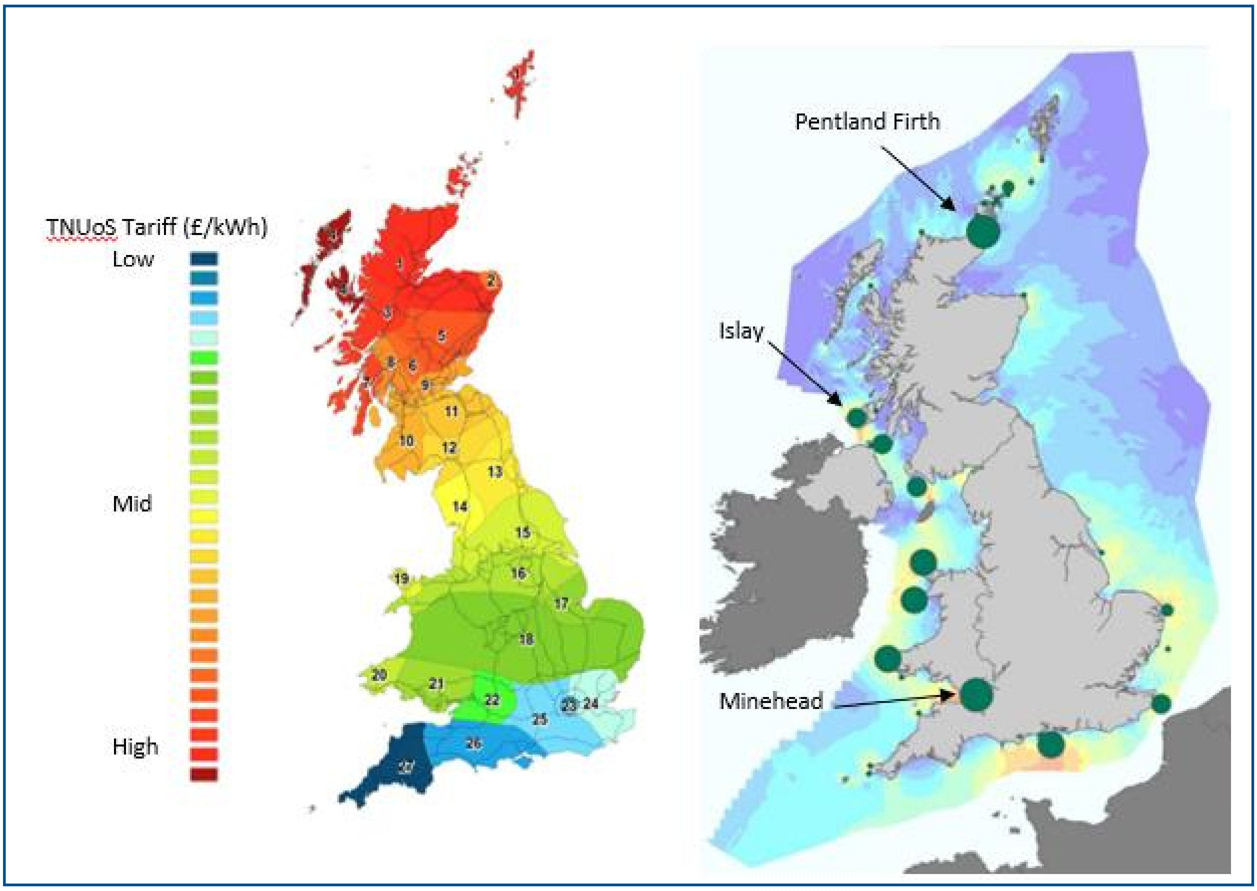

Figure 3: Comparison of TNUoS Tariff Zones (ITP Energised, n.d.) and UK TSE Potential (UK Parliament, 2020)

4.2.5 Innovation

Innovation becomes more important in reducing costs as the industry matures (ORE Catapult, 2021). Innovations that are already being progressed, or are scheduled for research projects include:

- Foundations: using a monopile foundation in place of a gravity-based one can reduce the steel requirement of a device by 90% (Coles [3], et al., 2021) and deliver a significant CAPEX saving
- Cable connections: Wet mate connectors allow electrical cable connections to be made sub-sea rather than on the installation vessel, simplifying TSE module installation, halving installation time to around an hour per module and the installation cost by 65% (Coles, 2019). It requires accurate alignment of the two halves of the cable, but innovation has also been achieved in this area (SAE, 2023).
- Control system upgrades: these will mainly deliver improvements to rotor efficiency through improved control. Promising areas of research include instrumentation to feedback incoming water conditions so that the blade torque, pitch and yaw can be adjusted to react better to incoming turbulence (Coles & Walsh, 2019).
- Structure and next generation materials: these include advanced manufacturing and design for existing blades; investigation of novel reaction system technology; turbulence intensity and wake effects investigation; new and improved blade technology investigation; testing novel reaction system designs at part-scale; novel materials to reduce biofouling, corrosion, and extended lifetimes (TIGER, 2022) (UK Parliament, 2020).

4.2.6 Infrastructure Investment

The TSE industry is dependent on the results of support auctions prior to making final investment decisions (FIDs) on projects. However, investment in manufacturing or logistical infrastructure takes many years and therefore is required prior to the support award. Smaller projects also may not be sufficiently large to justify investment on their own. Projects will not make investment decisions at the same time (and may not all be sanctioned), and future design evolutions may require additional works. There is therefore limited incentive within the industry to make the necessary investments, which slows investment and creates a “race to be second” culture.

An example of necessary investment is ports. Currently, UK port facilities can be a significant constraint, with many having insufficient water depths, inadequately reinforced quaysides, and/or insufficient space to assemble or store multiple modules. This will be exacerbated in areas which are seeing significant activity in other marine renewable projects, such as offshore wind. Resolution requires significant investment which would benefit multiple projects in a region, lead to job creation, and help level-up communities.

4.2.7 Marine Operations

As TSE commercial projects are commissioned in the late 2020s, there will be much opportunity to improve efficiency of marine operations, thereby reducing costs and improving understanding within the sector of how to proceed in a cost-effective way. There are a range of marine operations necessary for the installation, maintenance, and decommissioning of TSE assets, and there is opportunity to reduce the LCOE of TSE through standardising and optimising these operations.

Examples include:

- Mobilisation Days: It has been estimated that a 36-turbine array reduces mobilization and de-mobilization days per turbine by 26% relative to a four-turbine array, with a similar level of vessel cost saving expected (Goss, 2021).
- Bespoke vessels: a move away from expensive jack-up and dynamic positioning vessels can be achieved by designing ships to handle the specific requirements of TSE installation and will be economic if the industry develops a consistent project pipeline. Some examples of this already happening are described in literature (Goss, 2021).
- Installation, Operation, and Maintenance: Floating devices are fundamentally cheaper and easier to deploy than fixed turbines as they can simply be towed to location. However, as for wind, the floating technology is

less developed at the moment and so these are longer-term considerations. Bespoke vessels could also be designed and utilised to install large numbers of fixed seabed-mounted tidal turbines as the sector grows and the need for large-scale installation increases (Vivid Economics, 2019).

4.2.8 Project Lifetime

Life-extension activities, either during the design stage or through improved understanding of equipment integrity during operations, can increase the average lifetime of TSE projects, which would likely reduce the LCOE. In-life re-powering is one method of achieving this: some equipment (e.g. the electrical infrastructure) could be designed for a longer lifetime than the turbines and foundations, which could be replaced at intervals during the lifecycle of the project.

4.2.9 Site-Dependent Factors

Many LCOE cost drivers are site-specific and therefore more favourable sites with a lower LCOE will likely be developed first. This leads to a negative learning rate effect, where future sites are more challenging to develop and, in the absence of other factors, could have a higher LCOE.

4.2.10 Regulatory Constraints

The current market is constrained by several highly regulated processes, most notably seabed leasing, grid connections, and support (CfD) auctions. Whilst these processes have supported the development of new TSE projects since their inception, if they become too restrictive, they will negatively impact industry growth and the LCOE. Companies must bear the costs of unsuccessful projects, which materialises as either higher costs of finance or additional DEVEX in LCOE models. If there is insufficient long-term planning, and these processes are spread too far apart, a “feast and famine” industry will result, with limited incentives for long-term investment and further increasing supply chain stress.

4.2.11 Load Factor

Load factors (also called capacity factors) for future sites may increase from a combination of larger turbines, accessing sites with improved tidal resource and any improvements in system availability. This must be balanced against the effect of global blockage as array size increases. Array design can be optimised to minimise the impact of blockage effects. System availability is likely to improve due to greater use of digitalisation, predictive maintenance, and planning optimisation but may reduce if sites are less accessible or equipment maintenance requirements increase.

5 LCOE for TSE

As noted in Section 3, due to insufficient data from existing projects, a bottom-up cost model (the TCCM) was developed to produce scenarios for different TSE developments and their associated costs. This was refined via discussions with industry.

These costs were then input into the LCOE model to produce a LCOE range for TSE projects.

This section covers the development of TSE scenarios and their costs; discusses the breakdown of costs by project element (DEVEX, CAPEX, OPEX and DECEX) and shows the expected range of LCOEs for TSE project as Demo, FOAK and NOAK stages.

5.1 Component Costs for TSE Demo & FOAK Projects

Based on the evidence outlined above, the TCCM was constructed and populated to develop component cost estimates for four representative TSE projects - two Demo and two FOAK. Four cases provide an appropriate balance between giving a sufficient range of data whilst minimising computational effort.

The parameters of each case were developed based on the literature review and guidance from industry interviews and are shown in Table 2. Scenarios ranging from 18m to 24m rotor diameter and 1.5MW to 3MW rated power have been modelled previously to reflect the current state of the art developments in industry (Coles & Walsh, 2019). These selections are further supported by additional literature sources showing the size of currently installed projects in the UK and globally (Coles [3], et al., 2021).

Table 2: Demo and FOAK Case Parameters

Project Variables	Unit	Small Demo	Med Demo	Med FOAK	Large FOAK
Number of Turbines in Array	#	4	4	10	10
Turbine Power Output	MW	1.5	2	2	3
Rotor Radius	m	9	11	11	12
Total Array Power Output	MW	6	8	20	30

In both fixed and floating TSE, the scale of the devices varies substantially between projects. Fixed devices in the UK vary in scale from the 8m diameter 100kW Nova Innovation devices to the 18m diameter 1.5MW MeyGen devices, with industry plans to increase both the diameter and rated power further, following the trends seen in the wind industry (Coles & Walsh, 2019). Floating devices under development in the UK and abroad, show even greater variety in scale, with 4m diameter 70kW turbines on Sustainable Marine's PLAT-I device, up to 20m diameter 1MW turbines on Orbital Marine Power's O2 device. Many floating TSE devices are multi-rotor, with the latest designs mounting between 2 and 6 turbines on each floating structure. There is currently much greater variability in overall device design of floating TSE projects than for fixed projects, making 'typical' device costs less certain.

Whilst three of the four Contracts for Difference (CfD) in the latest round (EMEC, 2022) were awarded to multi-rotor floating projects, the floating TSE installed to date has all been single-device demonstrator projects. There is therefore very limited data available in the literature relating to the cost breakdown for floating TSE.

In contrast, 28 MW of fixed TSE capacity was awarded a CfD, accounting for over two-thirds of the 40.8MW of total CfD TSE capacity. This is a direct development from an earlier project (the MeyGen 1A project of three 1.5MW turbines mentioned above) for which there is substantial detailed data available (B&V, 2020).

For these reasons, the cases modelled in this section are based on data for bottom-mounted TSE devices. Floating devices would tend to have a higher CAPEX cost due to greater infrastructure complexity, but lower installation and maintenance costs, since they can be towed to site and easily lifted out of water. A reasonable initial assumption is therefore to assume LCOE for floating devices would be comparable with that for fixed designs.

All cases were assumed to have a standard turbine design with 3 blades and a gravity-base support structure with 3 feet, reflecting the turbines used in the existing Nova Innovation and MeyGen arrays. All cases were modelled using the same consistent project variables shown in Table 3. The project lifetime periods were determined through discussions with technology vendors and the discount rate of 9.4% applied was specified by DESNZ based upon previous economic analysis (Europe Economics, 2018).

Table 3: Demo and FOAK Case Fixed Data

Project Variables	Unit	All Cases
Design-Consenting Period	years	12
Pre-construction and Construction Period	years	4
Asset Lifetime	years	25
Decommissioning Period	years	1
Discount Rate	%	9.4%

5.2 Cost Breakdown by Lifecycle Stage

The costs of tidal stream projects can be split into four main lifecycle stages: DEVEX, CAPEX, OPEX and DECEX. The total estimated cost of each element, for the four cases modelled in the TCCM, are shown in Table 4. The total OPEX cost is the annual OPEX multiplied by the 25-year project lifetime.

Table 5 shows the percentage contribution of each element to the total project cost. It should be noted this is for indication only, as the contribution to the LCOE varies with the size of the array, and must account for the discount rate applied when costs are incurred across the project lifetime.

It can be seen from the tables that the vast majority of the total TSE project cost is driven by CAPEX and OPEX, and that DEVEX and DECEX are relatively insignificant. Interviews with industry have indicated that DEVEX is relatively independent of array size, so it will become increasingly insignificant with economies of scale, and DECEX is heavily discounted, so has minimal contribution to the LCOE. Reductions in CAPEX and OPEX are therefore key to reducing the LCOE of TSE.

Table 4: Cost Breakdown for TCCM Cases

Component	Bound	Total Estimated Cost (£ Million)			
		Small Demo	Med Demo	Med FOAK	Large FOAK
DEVEX	Lower	3.5	3.5	3.5	3.5
	Upper	5.0	5.0	5.0	5.0
CAPEX	Lower	54.4	58.2	97.4	199.4
	Upper	56.3	67.2	115.7	257.7
OPEX	Lower	36.1	38.3	62.8	125.1
	Upper	43.7	52.9	96.5	228.5
DECEX	Lower	0.8	0.8	1.4	2.8
	Upper	0.8	0.9	1.6	3.6
Total	**Lower**	**94.8**	**100.8**	**165.1**	**330.8**
	Upper	**105.8**	**126.0**	**218.8**	**494.8**

Table 5: Contribution of TSE Project Elements to LCOE

Component	% Contribution to Total Estimated Cost - Range	
	Demo Scale Tidal Array	FOAK Tidal Array
DEVEX	3 – 5	1 - 2
CAPEX	53 - 58	52 - 60
OPEX	38 - 42	38 - 46
DECEX	1	1

5.2.1 Components of DEVEX

Development Expenditure (DEVEX) covers design and consenting costs prior to the main financial investment decision (FID) and start of construction, relating to technical, engineering and design elements of the plant. It includes the costs of obtaining any licences required and meeting regulatory requirements prior to the start of the construction phase. Table 6 shows the percentage contributions of design and consenting costs to the total DEVEX cost for the cases developed in TCCM.

Table 6: Breakdown of DEVEX

Component	% Contribution to DEVEX - Range
Design Costs	56 – 60
Consenting Costs	40 – 44

Through engagement with technology vendors, it was found both the design and consenting costs are largely fixed for a tidal stream project. For consenting costs, a larger array requires a larger site, but the resulting consenting costs only increase by a small proportion. This is because the largest contributor to consenting costs is the cost of hiring a planning lawyer which is independent of the size of an array. The remaining and much smaller contributor to the overall consenting cost is due to the application fee, which is proportional to array size. For example, in Scotland the application fee is a banded rate dependent on the combined capacity of the array. A small demo project of <10MW combined capacity would have an £8.4k fee with environmental impact assessment (EIA) whilst a FOAK project of between 10-50MW total capacity would have a £42k fee with EIA (Scottish Government, 2022).

For the design costs, a demo project’s costs will be much greater than those for a FOAK project, providing the turbine design is not dramatically modified between the demo and FOAK. Therefore, the design costs of a demo project should be seen as an investment, resulting in reduced design costs for future projects. Once a design is established, the design costs per MW are further reduced as arrays are expanded. In summary, the larger the array and the more standardised the turbine design, the more a project will benefit from reduced DEVEX costs per MW and drive down the LCOE for future TSE projects.

It should be noted that whilst DEVEX has a small contribution to the overall project cost, the investment required to achieve the final design, with consents granted, carries the greatest risk for the developer before the FID is reached.

5.2.2 Components of CAPEX

Capital Expenditure (CAPEX) covers the procurement costs, materials, transport, assembly, installation and commissioning of the tidal stream array. It covers the expenditure that is incurred in the pre-construction period (the time from the signoff of the FID to the first installation of components on site) and the construction period (time from first installation on site to final commissioning (the date at which all turbines have supplied power to the grid on a commercial basis). Construction insurance is also required during this period as a CAPEX cost, in addition to the operational insurance which will be incurred as an OPEX cost.

The pre-construction and construction periods vary in length depending on the size and complexity of the individual project, but in total last typically 4 years from financial close to commissioning. This period is currently lengthy as a manufacturing facility must be established to produce the tidal turbines. In future, standardised turbine designs and pre-established manufacturing facilities will allow this time to be reduced and the manufacturing costs to decrease due to the benefit of economies of volume.

Table 7 shows the contribution of each project element to the total CAPEX for the cases developed in TCCM.

Table 7: Breakdown of CAPEX

Category	Component	% Contribution to CAPEX - Range			
		Small Demo	Med Demo	Med FOAK	Large FOAK
Materials	Turbine	25 – 39	30 – 49	37 – 58	50 – 71
	Foundation and base support structure	4 – 16	4 – 15	4 – 18	4 – 17
Other	Including onshore facilities, electrical balance of plant and cabling	57 – 59	48 – 55	38 – 46	25 – 33

5.2.3 Components of OPEX

Operational Expenditure (OPEX) covers the costs incurred during the lifetime of the tidal stream array. The operational lifetime of assets is typically 25 years. Table 8 shows the contributions of different elements of OPEX to the total OPEX cost incurred across the asset lifetime.

Table 8: Breakdown of OPEX

Component	% Contribution to OPEX - Range			
	Small Demo	Med Demo	Med FOAK	Large FOAK
Fixed OPEX	60 - 70	59 - 71	56 - 72	52 - 74
Grid Costs	0 - 12	0 - 13	0 - 18	0 - 23
Insurance	28 - 33	28 -33	26 - 34	25 - 35

There is little data available to infer the variable OPEX costs of tidal stream projects or the split of OPEX costs between fixed and variable OPEX. Therefore, for the purposes of this report, based upon the data available in literature and discussions with industry, the fixed OPEX costs will include all OPEX costs other than grid costs and insurance, i.e. onshore facilities, operations, spares, maintenance and repairs.

OPEX is likely to vary greatly between projects dependent on the distance from the project to the maintenance facilities and the meteorological and ocean conditions at the site. (Vazquez & Iglesias, 2016). The greater the distance from shore, the longer it takes to get staff and materials to site, the vessel hire period needs to be longer, and the wider the weather window needs to be. More severe weather and sea conditions may cause problems requiring more frequent maintenance, and also increase the difficulty of carrying out that maintenance.

Some of the OPEX costs will also be dependent on the turbine type deployed, as this will affect how heavy the device is and therefore the marine services and equipment required for deployment. The use of wet mate or dry mate connectors will also affect the cost of maintenance operations on cables and associated equipment. This was discussed in more detail in Section 4.2.5.

5.2.4 Components of DECEX

Decommissioning costs (DECEX) cover the cost of decommissioning the plant at end of life and removal of materials for reuse, recycling or as waste. Due to the infancy of the tidal stream industry, there is very little data available regarding the decommissioning of a commercial scale array. However, discussions with industry suggested the cost of decommissioning is expected to decrease per MW for large arrays. DECEX figures for the TCCM were developed based on (B&V, 2020) and industry discussions.

5.3 LCOE for Demo and FOAK TSE Projects

The costs and other parameters generated in Sections 5.1 and 5.2 were input to the LCOE model to produce LCOE figures for Demo and FOAK TSE projects. Figure 4 and Table 9:LCOE for Demo and FOAK TSE Projects, 2020 Prices show the resulting LCOE range.

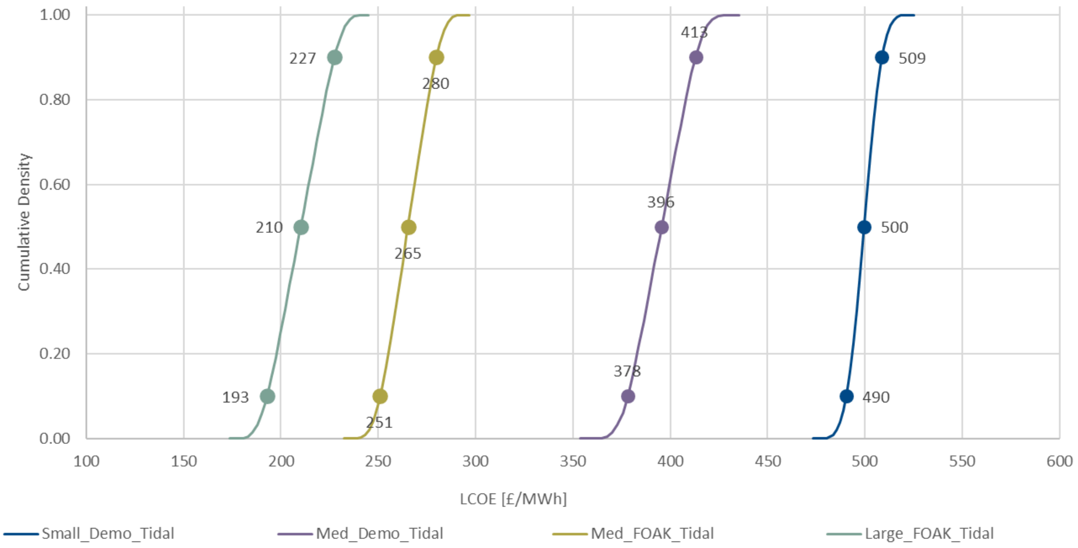

Figure 4: Demo and FOAK LCOE of TSE in 2020 Prices

Table 9:LCOE for Demo and FOAK TSE Projects, 2020 Prices

Percentile	LCOE (£/MWh)			
	Small Demo	Med Demo	Med FOAK	Large FOAK
P10	490	378	251	193
P50	500	396	265	210
P90	509	413	280	227

5.3.1 Sensitivity Analysis on Demo and FOAK Cases

This section indicates the impact of changes to some of the main cost drivers discussed in Section 4.

5.3.1.1 Impact of Current Macroeconomic Conditions

Figure 5: Demo and FOAK LCOE of Tidal Stream in 2023 shows the LCOE for the four cases developed using the TCCM to predict the cost of a tidal stream project in 2023. These results provide the estimated LCOE under current macroeconomic conditions, by adapting the baseline results for 2020 (shown above in Section 5.3), based upon discussions with technology vendors. The results show the combined effect of inflation between 2020 and 2023, as well as further increases in CAPEX and OPEX costs due to supply chain issues and increased material costs.

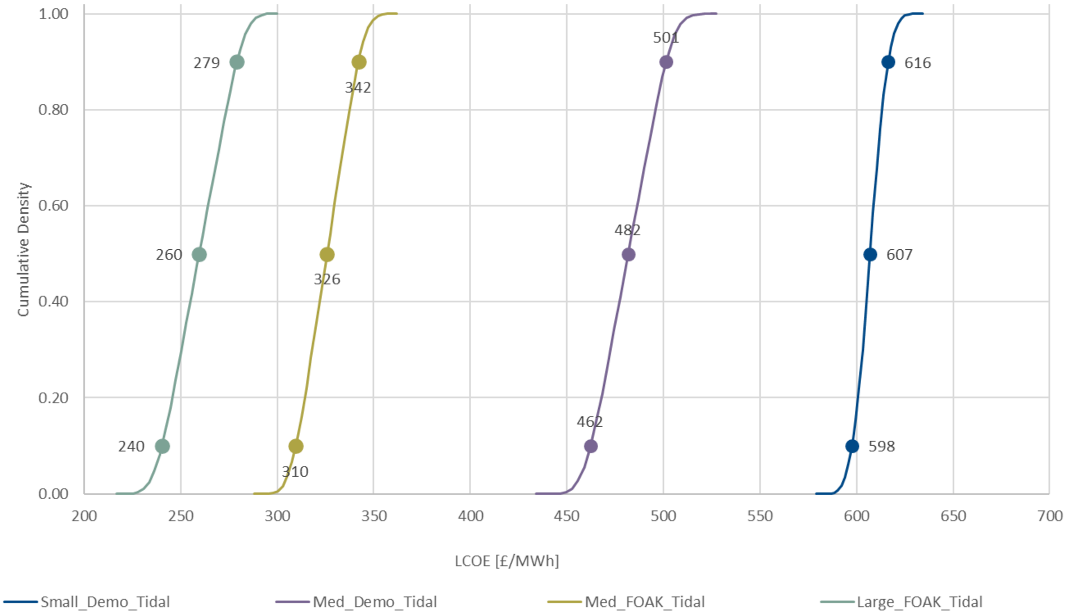

Figure 5: Demo and FOAK LCOE of Tidal Stream in 2023

5.3.1.2 Impact of Discount Rates

The results presented so far in the report use a discount rate of 9.4%. However, discussions with industry have indicated a rate of 13-15% is more realistic and reflective of the current state of the industry, due to the risk of investment in technologies before the design has become standardised and well demonstrated. in order to achieve the predicted discount rate in the region of 9.4%, standardisation across the industry and purpose-built manufacturing facilities are required.

Figure 6 shows the resulting LCOE when a discount rate of 13% is applied to the LOCE estimate for the current macroeconomic conditions (as per Figure 5). Comparison of the two figures shows that the results are heavily influenced by the discount rate applied and the resulting LCOE increases significantly using the higher rate.

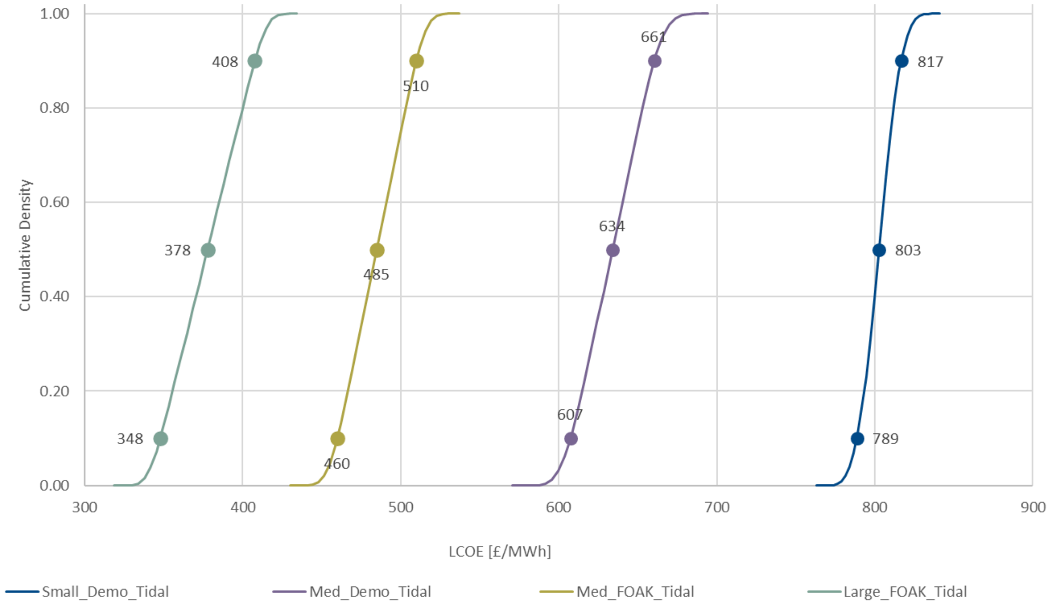

Figure 6: Demo and FOAK LCOE of Tidal Stream in 2023 with Increased Discount Rates

5.3.1.3 Impact of Grid Costs

As discussed in Section 4.2.4, grid costs vary depending on where a TSE project connects to the GB network.

Figure 7 shows the impact on LCOE of grid costs of zero and a feasible maximum of £80k/MW/year, in contrast to the Medium FOAK case. (The range used in the FOAK case was £0 to £37,076/MW/year.)

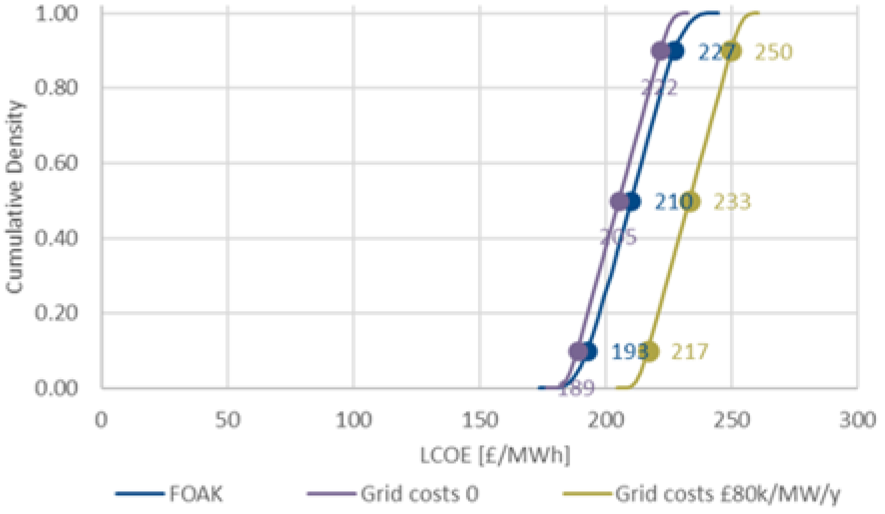

Figure 7: LCOE Sensitivity to Grid Costs

5.3.1.4 Impact of Asset Lifetime

The lifetime of a TSE array is assumed in the foregoing analysis to be 25 years. However, discussions with industry have indicated that some sites may not be able to afford to generate beyond the lifetime of their CfD (15 years) unless additional financial support is found. As a contrast, life extension beyond the originally budgeted 25 years may be possible.

The impact of these is shown in Figure 8, relative to the Medium FOAK case.

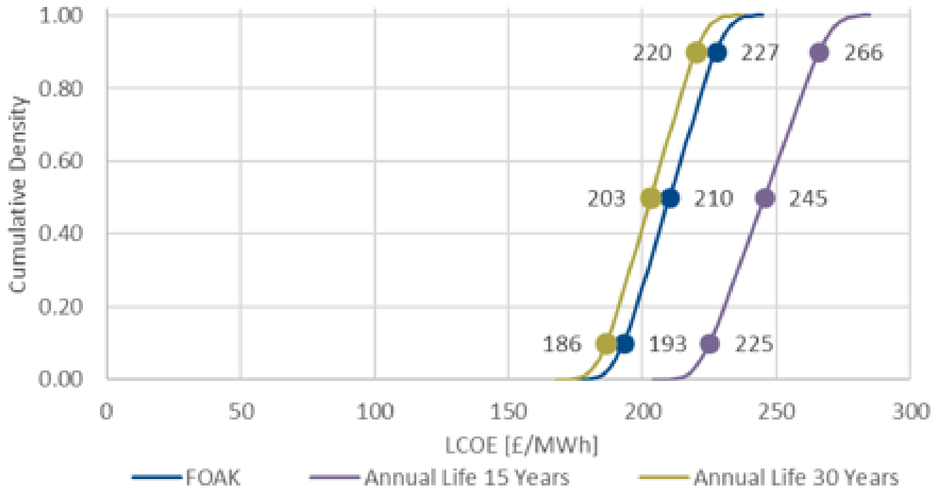

Figure 8:LCOE Sensitivity to Asset Lifetime

5.4 LCOE for NOAK TSE Projects

The inflation-adjusted LCOE of TSE installations will tend to reduce over time as a result of various factors including larger turbines and arrays, improved design, better O&M strategies and increased standardisation of components.

There are different approaches that can be taken to project future technology costs. One of the most detailed analyses has been carried out by the US National Renewable Energy Laboratory (NREL) (Shields, et al., 2022), which looks to develop a cost projection model for offshore wind energy.

The NREL analysis considers the different options for generating cost projections for emerging technology and discusses the advantages and disadvantages of each. That summary is shown in Table 10 below.

Methodology	Resolution	Advantages	Limitations
Learning Curve	Low	Empirical data basis	Top-down model
Expert Elicitation	Medium	Contextual data	Subject to survey biases
Bottom-up Assessment	High	Clearly Documented	High data requirement
Auction Results Analysis	Low	Public & commercial data	High data requirement

Table 10: Advantages and Limitations of Cost Projection Methodologies (NREL, 2022)

NREL find reasonable agreement between the trends produced by the different models but note that it can be unclear what implicit assumptions are used in deriving the projections, and that it can therefore be difficult to separate out the different components (technological development, financing improvements, supply chain maturity etc) driving the cost reductions. Taking account of these factors: the difficulty attributing drivers; the advantages and limitations of each approach discussed above; and, the limited historical data available, NREL propose a learning curve model for cost projection of FOW.

In this model, the 'learning rate' (LR) is defined as the cost reduction factor that can be expected for a doubling of the installed capacity of the technology. In the NREL case, the capacity growth rate used is the global one - this allows a greater range of project datasets to feed into the analysis and reflects the general assumption that as an industry with a global supply chain, industry learning from offshore wind projects on one continent will feed through to other parts of the world.

It is reasonable to consider an equivalent approach for TSE. TSE is also a developing industry, albeit at a lower maturity than wind, and there is even less historical data to rely on.

However, TSE is also subject to several constraint factors that do not apply to wind – for example, the maximum diameters of TSE turbines are much more restricted, due to water depth and clearance issues, and the number of exploitable sites is smaller. There are also several turbine design concepts, so TSE is subject to more design variations than FOW. Given the limited historical data, it is not fully known how these factors will affect the learning rate. However, as learning is best done by repetition, any differences between TSE installations will tend to reduce the savings that can be made via lessons learnt on previous projects.

We have attempted to address these issues by looking at TSE NOAK costs from two perspectives – a 'top-down' learning curve analysis, and a 'bottom-up' analysis. These are described in the following sections.

5.4.1 Learning Curve Analysis

There is limited LR data on TSE in the literature. However, the ORE Catapult produced a study (ORE Catapult, 2018) that compares the results of the Arup investigation (ARUP,for DECC, 2016) with wind industry LRs and finds them reasonable. These LRs are 11% (Low), 15% (medium) and 19% (high).

A cross-institution review (Coles [3], et al., 2021), covering multiple publications, summarised the projected learning rates in the TSE industry, the installed TSE capacity to date and the projected cumulative capacity to 2050 in the UK and globally (excluding the UK).

It found that learning rates within the TSE industry are typically projected to be between 9% and 17% (for CAPEX and OPEX) with each doubling of capacity. Some literature reported an initial learning rate of up to 25%, however this is viewed as too optimistic to be applied over the longer term.

For our LR analysis, we have used the rates discussed by the Catapult.

We have also followed the NREL approach for capacity growth, using global figures. Again, there are limited forecasts for TSE capacity beyond 2030, however the Energy Technology Partnership (ETP) (ORE Catapult, 2018), and Royal Society (RS) (Coles [3], et al., 2021) present some figures. These broadly agree, but the ETP is more front-loaded than the RS. They also broadly align with other forecasts up to 2030 and with the IRENA numbers 2030-50. The IRENA numbers show global installed TSE capacity doubling 7 times in the period from 2025 to 2050.

10.4MW of TSE capacity has been installed to date, and the Offshore Renewable Energy Catapult have projected that up to 1GW of TSE could be installed by 2040 (ORE Catapult, 2018). This is equivalent to the capacity doubling 6-7 times.

There are several TSE developers who foresee the potential to expand to the GW scale, although detailed plans and timelines are unclear. However, three tidal projects totalling 41.24 MW were awarded CfDs in the recent AR4. If built as planned by 2027-30, these would represent approximately 2 doublings of installed TSE capacity from its current level of 10.4MW.

Based on the above, it is our opinion that this cumulative deployment level is achievable by 2050 (a slightly longer timescale than predicted in 2018). However, his will require adequate support for the TSE industry in its early stages.

A 7x capacity doubling was therefore taken as our 'central' growth forecast. To indicate the sensitivity around this and allow some consideration of optimism bias, we also defined a lower growth rate which assumes a five-fold doubling of capacity.

Based on this analysis, four 'simple' scenarios and two 'profiled' scenarios were modelled. The 'simple' scenarios applied a single capacity growth rate and a single learning rate across the whole 25-year period, whilst the 'profiled' scenarios attempted to allow for the literature review finding that most learning is likely to be in the early years of the industry, reducing over time as the industry embraces increased standardisation of proven technology as it matures. The two scenarios reflect the two different literature sources, 5 aligning with ETP (ORE Catapult, 2018) and 6 with RS (Coles [3], et al., 2021).

The scenarios are described in Tables 11 & 12 below.

Table 11: NOAK LCOE – Simple Scenarios

Scenario	Years	Learning Rate (LR)	No. of times capacity doubles during the period	Comments
1	2025-2050	15%	7	central LR, central growth
2	2025-2050	15%	5	central LR, lower growth
3	2025-2050	19%	7	high LR, central growth
4	2025-2050	11%	5	low LR, lower growth

Table 12: NOAK LCOE – Profiled Scenarios

Scenario	Years	Learning Rate (LR)	No. of times capacity doubles during the period	Comments
5	2025-2030	19%	2	central growth, LR decreases as sector matures
	2030-2040	15%	3	
	2040-2050	11%	2	
6	2025-2030	19%	1	central growth, weighted to back end, LR decreases as sector matures
	2030-2040	15%	3	
	2040-2050	11%	3	

The model was re-run, applying each scenario to the central FOAK cost discussed above. This gave the following results for 2050 TSE LCOE. (Note that Scenario 5, which aimed to reflect the growth pattern assumed by ETP produces the same

LCOE results as Scenario 1, so it is not shown on the graph. It is also noted that using the low LR of 9% mentioned above (Coles [3], et al., 2021), and a 7x capacity doubling, gives approximately the same cost outcome as Scenario 4.)

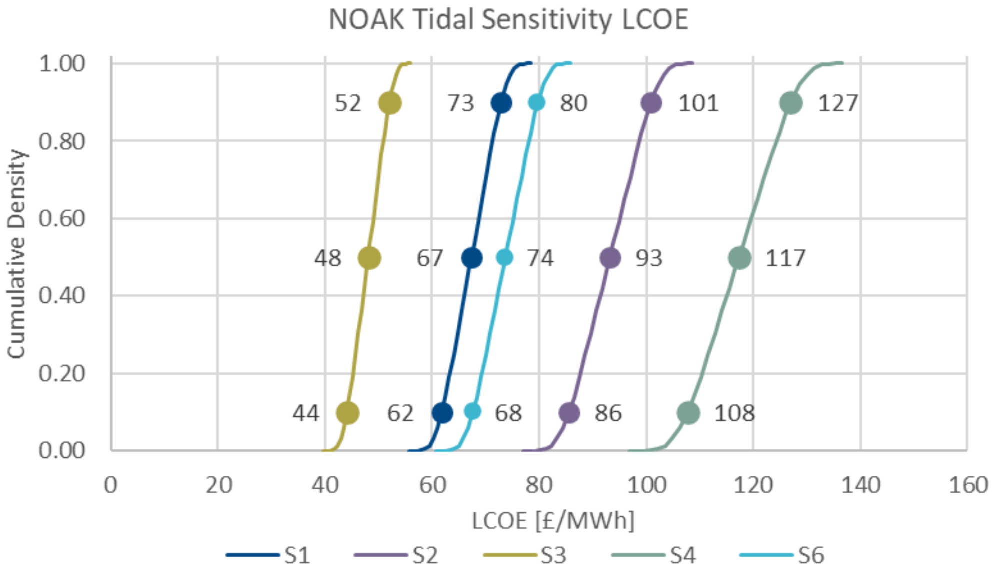

Figure 9: NOAK (2050) LCOE of TSE in Different Learning Curve Scenarios

The results generated by our model can be compared to the outputs from the TIGER study (TIGER, 2022).

Our current-year figures for a large FOAK installation are £260 ± 20/MWh (p10:p90 range), so are very closely aligned with TIGER's forecast, which is £259 ± 30/MWh. For 2050, our forecasts are more pessimistic than TIGER's, which forecasts that £50/MWh is achievable by 2047. We achieve £48/MWh by 2050 only by applying the most optimistic (19%) of the three learning rates we selected for the whole period up to 2050. The profiled scenarios, which aim to reflect projected TSE developments more closely, give a p10:p90 range for 2050 of between £62/MWh & £80/MWh.

5.4.2 Bottom-Up Analysis

To conduct a bottom-up analysis, a combination of commentary from key industry players, literature review and in-house domain knowledge has been used to guide updated inputs into our TCCM. These NOAK inputs reflect a range of likely deployment scenarios of tidal arrays in 2050. Since there was a great degree of uncertainty in the upper and lower bounds of the array specifications and costs in a 2050 scenario, the LCOEs presented in this section are P50 values only. Instead of providing a distribution of P10 to P90 NOAK predictions, a sensitivity study has been carried out to demonstrate the extent to which the most significant cost drivers outlined in Section 4 may reduce the LCOE of TSE by 2050.

The analysis considers the impacts of economies of volume and economies of scale, and how these drive cost reduction from FOAK to NOAK scenarios.

Economies of volume are found as the industry moves to commercial scale projects, and the number of turbines within an array increases. Larger arrays produce more energy and benefit from lower costs per turbine due to fixed costs being spread across more devices. While CAPEX and OPEX per MW will continue to fall as the size of the array increases, the load factor for TSE will also fall due to blockage effects and variation in velocity across a tidal site (Goss

2021). Therefore, the optimal LCOE for TSE will be achieved at mid-sized arrays, where the benefits of lower CAPEX balance the reduction in power factor due to blockage effects.

Economies of scale are found as the TSE devices increase in size. It has been demonstrated that increased rotor diameter and rated power can lead to a significant reduction in LCOE, because the increase in cost of larger scale devices is outweighed by a larger increase in yield (Coles & Walsh, 2019) (ORE Catapult, 2018).

Table 13 shows how the predicted NOAK LCOE for two different turbine designs varies as the **number of turbines** in an array is increased. It will be seen that the optimal LCOE is achieved for arrays of around 75 turbines, and is £114/MWh and £97/MWh for medium and large-scale turbines respectively. To move towards these larger scale projects, developers could cluster multiple arrays in a given region - for example either side of an island - using layout optimisation to minimise blockage effects.

Table 14 shows the impact of **increasing the turbine scale** on the P50 LCOE predictions for an array with 75 turbines and NOAK/2050 cost levels. It shows that increasing the turbine diameter generally has a larger impact on the LCOE than increasing the rated power. This is because increasing the diameter increases power generation in lower velocity tidal flows, whilst increasing the rated power increases the power generation in higher velocity flows. Once the rating is high enough to exploit the highest velocities seen in UK TSE sites, there are diminishing returns on increasing the rated power further. While increasing the diameter could have a notable impact on the LCOE, there are limited locations around the UK which would be suitable for 26m diameter turbines. Flow is fastest in shallower waters due to conservation of mass, and there are often clearance requirements above and below the turbines, which would make larger turbines impractical. Furthermore, interviews with industry indicated that standardisation of turbine design is expected to have the most significant impact on reducing turbine costs. It is therefore likely that the industry will focus on turbine specifications that are suitable for a range of sites across the UK, rather than the extremes of design presented in Table 14.

Table 13: Cost Impact of Economies of Scale and Volume on NOAK/2050 LCOE (£/MWh)

			Number of Turbines			
Turbine Scale	**Capacity (MW)**	**Rotor diameter (m)**	**25**	**50**	**75**	**100**
Medium	2	22	123.9	115.0	114.0	115.4
Large	3	24	103.7	97.4	97.0	98.5

Table 14: Impact of Turbine Specifications on NOAK/2050 LCOE (£/MWh), 75-Turbine Array

Turbine Diameter **Turbine Rated Power**	**22m**	**24m**	**26m**
2MW	114.0	105.0	98.2
2.5MW	109.4	99.4	91.9
3MW	108.3	97.0	88.7

Finally, we consider the scaling factor. As described in A.2.1.3 an 85% scaling factor is applied to the load factor in the TCCM to account for availability and efficiency losses. As the industry progresses these losses are likely to reduce. This would indicate that a higher scaling factor could be more appropriate for NOAK installations. The impact of this scaling factor on LCOE is demonstrated in Table 15– increasing the scaling factor to 90% results in a 5.5% reduction in LCOE, for both medium and large-scale turbines.

Table 15: Impact of reduced losses on NOAK P50 LCOE (£/MWh), 75-turbine array from Table 13

	Scaling Factor	
Turbine Type	**85%**	**90%**
Med: 2MW, 22m	114	108
Large: 3MW, 24m	97	92

The bottom-up analysis gives higher LCOE values (£92-114/MWh) than the learning rate analysis (£62-80/MWh). This is unsurprising as the former focuses on the TSE components, and does not account for project-level learning which is implicit in the latter. It is useful to compare the two analyses however, as doing so gives an indication of the range of outturn LCOE values that could apply to TSE NOAK projects under different scenarios. The bottom-up analysis indicates a feasible yet conservative scenario, whilst the LR analysis attempts to include all the applicable cost-reduction mechanisms, albeit using a 'broad-brush' approach.

Given the limited historical data and the current position of TSE developments it is recommended that the LR analysis figures are used in forecasting at the present time. As the projects awarded AR4 contracts, and other TSE projects worldwide, come on stream over the next five years, more data will become available, and the cost reduction trajectory will become more discernible.

5.5 Technological Changes Likely to 2050

As there is no 'standard site' for TSE, it is not expected that a single design will become the standard for all projects (in the UK, or worldwide). Module and turbine designs will continue to evolve and, although a considerable consolidation in the supply chain is anticipated, designs with either concrete or steel as the primary material are expected to be developed dependent on the relative benefits of these materials in different regions of the world. Mooring systems will also remain site-dependent, and although significant advances in dynamic power cable designs and subsea connections are expected, it is unlikely that one cable design solution will suit all sites.

As has been discussed previously in this report, the trends which are being seen in TSE and which will contribute to cost reduction over the next 25 years are:

- larger turbines, both in terms of rotor diameter and rated power
- larger arrays, and array layout optimisation to minimise blocking effects
- a move away from gravity-based foundations to monopiles for fixed devices
- installation of multiple rotors on a single supporting structure, whether fixed or floating

Turbine design is likely to change between FOAK and NOAK stages, as cost reduction becomes more important and design margins are optimised. This will remove a degree of over-engineering that is often found in early-stage designs - future designs can be adjusted for known turbine loading and other mechanical parameters based on field experience gained to date.

TSE concepts which are currently at a lower TRL (such as Tidal Kites) will be developed further, but the development is at too early a stage to confidently predict the cost reduction potential for such devices.

Financing is a key area for project cost reduction. As knowledge of the TSE industry improves the perceived risks will decrease leading to reduced financing costs. However, it should be noted that financing costs may increase between Demo and FOAK projects. This is due to the increased risk involved in funding larger arrays when some aspects of the TSE technology or process are still considered relatively novel.

Another area of potentially significant innovation relates to developments in offshore substations, which in future will likely be based on subsea or floating concepts rather than the usual jacket structures.

The current model of building individual grid connections for each offshore site may evolve into an “offshore grid” with shared infrastructure and more centralised ownership. Whilst this may reduce overall costs, it would increase interface risks and could lead to concerns that projects are dependent on grid infrastructure that is outside the control of the developer. It will also rely on a number of projects being located in proximity to each other, although these could include other marine renewables such as offshore wind.

6 Summary

Component costs of LCOE for TSE and resultant LCOE distributions have been determined based on a review of literature and industry engagement. A sensitivity analysis has been carried out to demonstrate the impact of uncertainty in key variables, and a qualitative description of cost drivers is provided. These findings are provided in a combination of this report and its accompanying spreadsheet.

The LCOE for TSE is expected to rapidly decrease due to a combination of factors, most notably the cost of finance, and economies of scale and volume. However, there are numerous influencing factors which could increase or decrease this rate of cost reduction, including the rate of TSE growth. Several of these factors are controlled by legislation and therefore government policies have significant influence over the LCOE.

Overall, there is significant uncertainty over future LCOE for TSE as demonstrated by comparing Figure 4: Demo and FOAK LCOE of TSE in 2020 Prices and Figure 6, which shows a potential increase of up to 83% to the LCOE based on a change in macro-economic conditions and an increase in discount rates to those currently being offered to the TSE by financing providers. This indicates the scale of the opportunities and risks for TSE technology.

The TIGER report "*Cost reduction pathway of tidal stream energy in the UK and France*" (TIGER, 2022) gives a comprehensive summary of technical innovations that are being developed, and that will contribute to the cost reduction of TSE in the longer term.

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Annex A - Appendices

A.1 Technology Readiness Level (TRL)

Technology Readiness Level (TRL) is an indication of the maturity of a particular technology. The original concept was developed by NASA for space systems in the 1970s and in 2013 the TRL scale was incorporated into international standards via ISO 16290:2013. The scale ranges from 1 to 9 with TRL level 1 being at the basic research stage and TRL level 9 being a complete actual system that has been proven through successful operation.

Since its original definition, the TRL scale has been adapted for use in many other industries. EMEC has a TRL scale on its website which relates the TRL concept to marine energy applications[1], and this is also reflected in UKRI funding guidelines[2]. The TRL scale is shown in Table A1.

Table A1: Technology Readiness Levels

TRL	Definition	Development Stage
1	Basic principles observed and reported	Applied and strategic research
2	Technology concept and/or application formulated	
3	Analytical and experimental critical function and/or characteristic proof of concept	
4	Component and/or partial system validation in a laboratory environment	
5	Component and/or partial system validation in a relevant environment	Technology validation
6	System/subsystem model validation in a relevant environment	
7	System prototype demonstration in an operational environment	System validation
8	Actual system completed and service qualified through test and demonstration	
9	Actual system proven through successful operation	

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[1] https://www.emec.org.uk/services/provision-of-wave-and-tidal-testing/pathway-to-emec/technology-readiness-levels/

[2] https://www.ukri.org/councils/stfc/guidance-for-applicants/check-if-youre-eligible-for-funding/eligibility-of-technology-readiness-levels-trl/

A.2 Methodology Details

This section contains details of the approach used by Frazer-Nash to model the LCOEs for TSE.

A.2.1 LCOE Model Setup & Data Gathering

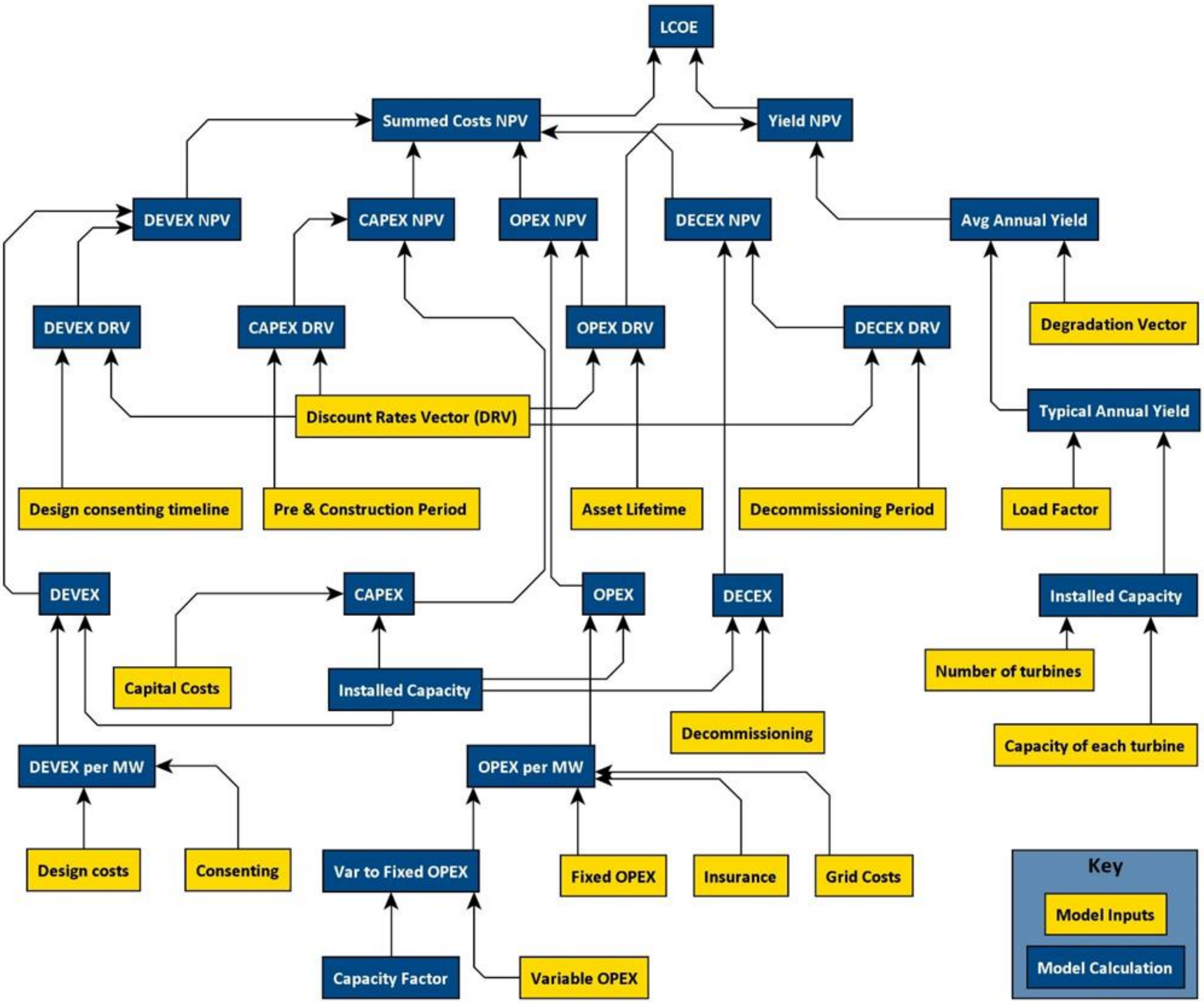
Prior to starting any data gathering, a draft LCOE model was set up to clarify the inputs required, and to ensure that data obtained would be at a relevant level of detail. Data was then gathered from a literature review of publicly available information, including previous work carried out for DESNZ, as well as through industry engagement.

A.2.1.1 LCOE Model Setup

An Excel-based probabilistic graphical framework model was developed to calculate LCOE and align with the granular inputs required for the associated spreadsheet provided by DESNZ (BEIS, 2023). To aid model transparency, a dependency map was first drawn. Figure 10 shows the dependency map; this provides a visual description of the relationships between all the factors which inform the output (LCOE). This dependency map was replicated within our model, with probability distributions assigned to inputs and relationships captured as calculations.

The key advantage to the probabilistic graphical framework approach is it allows the inherent uncertainty in input assumptions to be captured via probability distributions. These probability distributions propagate through the model calculations to provide output distributions which can be presented as low, medium, and high estimates.

The probabilistic graphical framework also enables us to perform Sobol analysis. Sobol analysis is a form of variance-based sensitivity analysis which allows the variance of the model outputs to be decomposed into fractions which can be attributed to inputs. This lets us quickly identify sensitive variables.



A.2.1.2 Literature Review

Around 30 reports and papers on TSE were reviewed (see References section). Various data were extracted including costs, sensitivity and variability information, and barriers and cost reduction opportunities.

A.2.1.3 Establishing Baseline TSE Component Costs

Due to the small number of existing projects and companies involved in TSE scheme development, there was understandable reluctance among industry sources to share detailed cost data from existing projects. There were also some concerns from the industry over how the data might be used, and whether it would be kept in context.

Using data from the literature review, FNC therefore developed a TSE component cost model (TCCM) to generate costs for example TSE projects.

It is based on MW-scale fixed-bottom TSE designs due to the greater availability of data in the literature and higher levels of engagement from developers of fixed-bottom turbines and arrays. It took initial data from (Coles [2], et al., 2021) and (B&V, 2020) and was further refined following discussions with technology vendors and TSE scheme developers. These discussions were focussed on how costs could evolve in future and industry challenges and opportunities.

The TCCM considers a number of project variables, including:

- Number of blades
- Rotor Radius
- Turbine power output
- Number of ballast blocks
- Number of feet
- Number of turbines in array
- Total array power output
- Load Factor
- Operating life

An 85% scaling factor is applied to the load factor to account for availability and efficiency losses.

It can model costs for various turbine and array sizes, and can also be used to model the reduction in costs due to economies of volume (based on literature and input from interviews with the TSE industry on bulk discounts, standardisation and other cost savings) and the reduction in load factor due to blockage and variation in velocity across a typical tidal site (based on data from models of multiple typical tidal sites around the UK). It can also model the change in costs due to turbine design, so can be used to test the impact on LCOE of increasing rotor diameters and rated powers to the upper limits seen in literature. It models the increase in cost, and increase in power generation, based on representative power curves of turbines of each design and typical flow distributions of key TSE sites around the UK.

A.2.2 Data Categorisation & Initial Modelling

Projects to be modelled were divided into three categories according to the following definitions:

1. 'Demo' – Demonstration stage projects, aimed at proving a particular design in the marine environment and understanding its operational parameters. These projects tend to be relatively close to shore and have a single turbine or a small array of around 5 modules. The initial SAE, Nova and Orbital projects mentioned in Section 2 fall into this category.
2. 'FOAK' – first of a kind commercial stage projects. These are larger than Demo projects and are run on a commercial basis, having an expectation of 25-year-plus lifetimes and typically comprising 10-15 turbines. The proposed MeyGen 2 installation would be in this category.
3. 'NOAK' – nth of a kind commercial stage projects. These are large-scale projects developing tidal energy farms at 100MW scale with upwards of 50 turbines, using mature, proven technology and drawing on experience from Demo and FOAK projects to minimise costs and maximise efficiencies. NOAK projects are anticipated to start coming on stream from the late 2030s onwards.

A note on "commercial" projects: with the availability of sufficient subsidies, it is possible for any projects (whether Demo, FOAK or NOAK projects) to be run on a commercial basis (i.e. to be run with the aim of being profitable). Project developers may be more willing to take more financial risk on smaller-scale (Demo) projects, and some Demo projects may deliberately be sanctioned despite likely being unprofitable due to other drivers (for example marketing a specific technology). It is considerably less likely, due to the larger volumes of money required, for FOAK or NOAK scale projects to be sanctioned on a non-profitable basis.

Initially the TCCM was used to develop component costs for four example projects – 2 Demo scale and 2 FOAK.

These data were then input into the LCOE model, to generate LCOE distributions for Demo & FOAK-stage TSE. The LCOE values produced were refined in discussion with industry.

A.2.3 Sensitivity Analysis

By adjusting specific model inputs, it is possible to carry out a sensitivity analysis of potential developments to the TSE industry. From industry interviews, literature review findings, industry experience and Sobel analysis of the LCOE model, a range of factors were identified. These were input into the FOAK LCOE model, and the results analysed.

A.2.4 Modelling LCOE for NOAK Projects

To model the LCOE distribution for NOAK projects, the TCCM input parameters were adjusted using data obtained from the literature review and industry discussion. These reflect technology changes that are likely to occur between FOAK and NOAK stages, and take account of the effect of larger arrays on resource capture (e.g. the impacts of tidal blockage, meaning output does not scale linearly with array size). They also take into account the impacts of ‘learning by doing’ as the installed capacity of TSE projects increases over time. A series of likely deployment scenarios were modelled, to generate input data for the LCOE model. This was then used in the same way as the Demo and FOAK data discussed in Section A.1.2.

To identify a reasonable lower bound of NOAK CAPEX, values from literature for costs of component parts only were used (Segura, 2017).

When modelling the NOAK projects, the durations of the different lifecycle stages were kept unchanged from those used for the Demo and FOAK projects (see Table 3). These periods may change as the industry matures, for example the design and consenting period may decrease and the operational lifetimes of projects may increase in line with developments observed in other offshore renewable energy industries. At present this is subject to considerable uncertainty and is dependent on regulations and technology developments and therefore it is not possible to estimate future values with certainty.

The outputs from the TCCM were input into the LCOE model in the same way as the Demo and FOAK data discussed in Section A.1.2 and resulted in a series of outputs which show the effect on LCOE of adjusting key variables (including turbine capacity, turbine rotor diameter and number of turbines within an array). Due to the increased levels of uncertainty in the upper and lower bounds of the array specifications and costs in a 2050 scenario, the LCOEs presented are P50 values only.

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