

A review of component and system reliability in tidal turbine deployments

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Abstract

Tidal stream energy has the potential to contribute to global renewable energy generation, but this remains largely untapped. Technical developments have helped create a nascent industry with several pre-commercial installations. However, planned projects experience a cautious investment climate due to perceived risk of failure, and maintenance and repair cost. This paper reviews 58 tidal stream energy deployments between 2003 and August 2020. The analysis reviews commonalities, success and engineering issues, to inform current and future projects. The work classifies each deployment by type, rated power, number of devices, grid connection and foundation. In each case, project status and (if appropriate) failure mode is identified. Failure modes are compared to deployment classification to identify potential relationships. Most deployments were of horizontal axis turbines. The majority (54%) of deployments performed well. 18% failed, 14% were withdrawn from service, and 14% generated less power than planned. The most common failure cause was blade failure, followed by generator and monitoring failures. Ducted devices and devices in high velocity locations were more likely to fail, suggesting that flow velocity is a key factor. Most blade failures were attributed to underestimation of loads during design. Floating deployments were less likely to fail than fixed deployments, but more likely to be curtailed. Off-grid and grid connected deployments showed similar failure rates, suggesting sector immaturity. Tidal stream energy has accumulated around 1.4 million operating hours. Analysis shows a falling empirical failure rate, and likelihood of failure similar to that experienced by the wind industry at a similar stage. This work will be useful for project planners, developers and technology companies and investors in de-risking future project efforts.

Highlights

- Tidal stream energy has accumulated 1.4 million operating hours since 2003
- 54% of deployments were successful, 18% failed, 28% were curtailed or underperformed
- Most failures were of turbine blades, and most related to underestimation of loads
- Floating support structure deployments were curtailed more often, but failed less
- The sector has an empirical failure rate similar to that of wind at a similar age

Keywords

Renewable Energy, Tidal Stream, Reliability, Reliability Growth, Failure Mechanisms.

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Word Count

Excluding titles, figure and table contents and captions: 8235 words

List of abbreviations

O&M: Operation and Maintenance

LCOE: Levelised cost of energy

HATT: Horizontal axis tidal turbine

VATT: Vertical axis tidal turbine

Cf: Capacity factor

kW, MW, GW, TW: kilowatt (1^3), Megawatt (1^6), Gigawatt (1^9), Terawatt (1^{12})

kWh, MWh, GWh, TWh: kilowatt-hour, Megawatt-hour, Gigawatt-hour, Terawatt-hour

1 Introduction

Tidal stream energy is currently the focus of a major research effort. Tidal stream energy describes the capture of the energy of tidal ebb and flow using devices placed in the tidal stream, without using barrages or lagoons to restrict flow. The predictability of the tides, and therefore of energy generation, means the technology has a key advantage over other renewable energy sources and does not require the provision of fossil-based backup generation, avoiding the so-called ‘intermitency problem’. The UK has around 50% of Europe’s tidal energy resource. Some studies[1] suggest technical and practical resources of 29TWh/yr and 20.6TWh/yr respectively exist at 30 key tidal stream sites in the UK. Various estimates have been made of the global tidal stream energy resource, suggesting potential between 64GW and 120 GW [2]. These figures are hypothetical estimates but nonetheless illustrate the significant potential of the technology, which is still largely untapped (as of 2019 global installed tidal stream capacity stood at 35.5MW[3], less than 0.06% of the lowest resource estimate).

One reason for the apparently slow development of the tidal stream energy sector is the challenge of operation and maintenance. In recent years there have been numerous technical developments, particularly in device design, which have allowed demonstration and pre-commercial deployments to take place. Many of these deployments have suffered from reliability issues resulting in failures, curtailed deployments, and lower-than-expected power generation. This has in turn led to a challenging investment landscape, with high investor risk due to the cost of operation and maintenance causing some planned deployments to be halted. Previous studies [2] report that in some cases operation and maintenance represents 30% of the total cost of electricity generation from tidal energy, whilst the most recent Energy Innovation Needs Assessment [4] published by the UK government estimates the value at 17% for floating devices and 43% for fixed devices. High O&M costs due to low reliability contribute to high levelised cost of energy (LCOE) for tidal stream energy, which limits the ability of the sector to compete with other forms of energy. To advance the sector, reliability must be improved in order to reduce these costs. The Energy Innovation Needs Assessment report estimates the current LCOE of fixed tidal stream energy as £300/MWh, and suggests the potential for this to reduce to £150/MWh at 100MW of deployment. To achieve this will require a significant reduction in O&M costs, and therefore an improvement in reliability.

1.1 Reliability

Reliability is defined as ‘the ability of an item to perform a required function under stated conditions for a stated period of time’ [5], or ‘to perform its required function without failure during a specified time interval’ [6]. The qualitative interpretation is that the item is free from operational failures. In quantitative terms, reliability is given as the probability that the function is performed for specified conditions and time. Thus, four aspects need to be defined to make a statement about the reliability of an item: The probability that the

item will operate, the function that is required, the operational and environmental conditions, and the period of time the function is required for. Operating conditions influence reliability and should therefore be stated in context of the reported performance. These conditions typically comprise the type (for example mechanical, electrical, thermal) and level of stress, the use rate, operating profiles and environmental conditions. Some previous studies [7] [8] [9] have considered the reliability of tidal stream energy, but unfortunately the operating and environmental conditions are rarely reported. This paper thus makes a concerted effort to collect and deduce as many operating variables as possible for each deployment.

1.2 Learning rates & Reliability growth

Learning rates are commonly used to describe the reduction in cost of energy generation brought about by learning. The learning rate for a given technology defines the fraction of cost reduction per doubling of installed capacity and is calculated by the cost difference between consecutive units of generation (i.e. if the first MWh of energy costs £100 to produce, and the second £90, the learning rate is 10%). Learning rates can be uncertain in the early stages of technology development due to a lack of robust cost data, but have been estimated by the Carbon Trust [10] to be around 10% for tidal stream energy. This work identified four key areas for this learning: Concept design developments; Detailed design optimisations; Economies of scale; and Learning in production, construction, installation and O&M. With a focus on O&M, the present work looks specifically at the reliability of devices in operation.

The concept of reliability growth was introduced by Duane [11]. This work established that for a given technology, reliability can be observed to improve (i.e. failure occurrence reduces) with operating hours. This improvement is observable in a number of now well-established technologies, such as the horizontal axis ‘Dutch model’ wind turbine. In contrast to this single technology design, which is dominant in the wind industry, the tidal stream energy sector currently encompasses a multitude of concepts with significant technical and operational differences. In this case, each concept may accumulate operating hours independently and pursue its own reliability growth path, rather than a single reliability growth path being followed by the sector as a whole. This may lead to the tidal stream energy sector following a slower reliability growth path than would occur with a single dominant technology, and thus having lower total reliability.

1.3 Aims

Failed and curtailed deployments are very challenging and disappointing for individual projects, but much can be learned from them to contribute to the understanding and mitigation of potential failure modes in future devices and deployments. This article aims to identify and classify the status and performance of all previous deployments of tidal stream energy converters, in order to highlight the most common modes of failure and identify any correlation between failure type and location, device type or design, or other project features. The work has reviewed as many deployments as possible and the authors are able to identify each, but the approach taken here in order to avoid ‘naming and shaming’ individual technologies, sites or developers, is to anonymise the data presented throughout. This article also aims to study the impact of the diversity of device designs on reliability and reliability growth.

2 Methodology

2.1 Device Classification

As noted by previous work on the subject (e.g. [12] [13] [14]), there are a wide range of machines designed to extract energy from the tides. This paper focusses on tidal stream energy, i.e. does not cover other types of tidal energy extraction such as tidal barrages, but the range of designs and technology concepts is still wide. Based on common distinctions in the literature and to facilitate subsequent comparison, five features were used to define the tidal energy devices considered in this study, namely:

- Extractor type (horizontal axis turbine, vertical axis turbine, or oscillator)
- Ducting (ducted or non-ducted)
- Mounting type (floating or fixed)
- Foundation type (moored, gravity base, piled, or shore-fixed pontoon)
- Device rated power.

For rated power three device size ranges were observed in previous deployments: Small scale research devices with rated power below 100kW, medium scale devices with rated power often around 300-600kW, commonly used during initial testing, and large scale devices with rated power commonly 1000kW, 1500kW or 2000kW. Devices were therefore classified into three categories:

- Small (sub-100kW)
- Medium (100kW or more, but less than 1MW)
- Large (1MW or larger)

These defining features allowed all the devices identified during this study to be classified. To aid the analysis of trends linking failure and device type, it was deemed important to be able to classify all devices in a true category, without using categories classified as ‘other’. The device classification categories used in this paper (excluding device rated power) are illustrated in Figure 1.

2.2 Deployment Classification

Each deployment was classified by considering the design of the tidal energy device as described above, and the location, duration, size and grid connection characteristics of the deployment. The number of turbines in the deployment was also recorded. Grid connection status was classified as off-grid, connected to a small grid such as an island, or connected to a national grid.

2.3 Data collection method and procedure

In order to review and classify as many deployments as possible, a wide range of data sources were considered during this work. The aim of the study was to establish a database of deployments, in order to subsequently allow the comparison and classification of deployment outcomes. There was significant variation in the level of detail available between deployments: Some deployments were the subject of numerous academic journal articles or technical reports meaning that extensive data on performance and reliability was available, whereas other deployments were mentioned in industry articles but were not the subject of any detailed publically-available information. Though the latter presented challenges in the capture of sufficient detailed information, no deployments were excluded due to a lack of information. The general information gathering procedure undertaken is illustrated graphically in the upper part of Figure 2.

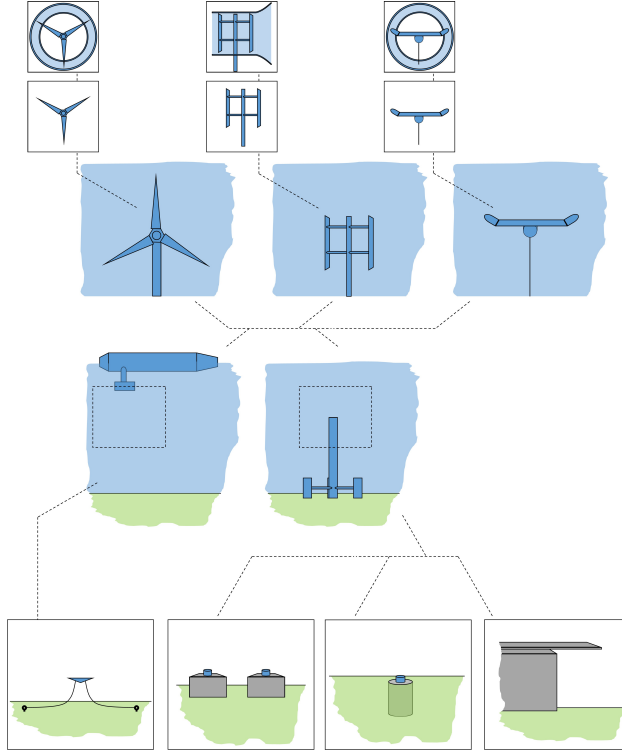


Figure 1: Device classifications. Top to bottom: Ducting (ducted or unducted), extractor type (l-r: horizontal axis; vertical axis; oscillator), mounting type (floating; fixed), foundation type (moored; gravity base; piled; pontoon)

The scope of the study was global. Information on deployments was searched for in academic literature (both on specific deployments and through technology or industry review articles), manufacturer press releases or notifications, government announcements, industry news resources, social media and general press. Relevant non-academic articles were searched for using the Google.co.uk search engine between 13th July 2020 and 18th August 2020, with the following search terms: ‘tidal stream energy installation’, ‘tidal stream energy deployment’, and ‘tidal stream turbine installation’. More general search terms were also used and their results filtered to include only tidal stream energy. The following additional terms were used: ‘tidal energy installation’, ‘tidal energy farm’, ‘tidal farm’. Where searches revealed information on a deployment, characterisation information described in Sections 2.1 and 2.2 was recorded in a spreadsheet. When a search highlighted a deployment not previously documented, it was often necessary to conduct further searches using specific terms in order to capture all these details. In the majority of cases, initial details of deployments were revealed through the search procedure described above, and academic literature searches were then used to capture additional details. Academic literature searches were undertaken using Web of Science [15]. The same search terms were again used, as well as specific search terms to capture details of specific deployments which were not included in initial information. For example, it was often the case that an initial search would reveal a description of a deployment in a manufacturer or developer’s press release, or an article in an industry website such as Offshore Energy [16], but this initial description would not include detailed information on, for example, the device rated power or foundation system. Using the details of the deployment from this initial article, an academic literature search would often provide an article which included these details. Ultimately, the data captured for each deployment was, in the majority of cases, made up from a diverse range of sources. The findings of this study rely on the reliability and accuracy of the reported data, and the potential for overstatement or the accidental reporting of incorrect data was considered. Here the diversity of data sources is a benefit, since cross-checking of data from different sources

on the same deployment was possible. In the case of academic publications, accuracy should be ensured by the peer review process, and by legal obligations and industry standards (e.g. for power output reporting) in the case of manufacturer published information. At this stage it has not been possible to deduce a numerical confidence interval for the data, but as the database grows and further deployments are added and published data can be compared to raw measured values, this may be achievable.

2.3.1 Previous Reviews

During the search procedure described in Section 2.3, a number of books, websites, articles and reports were found which included a review or list of tidal energy deployments. These resources (e.g. [17] [18] [12] [13] [19] [8] [9] [20]) were cross-referenced against the deployments found during the initial search to ensure all which had reached the deployment stage were included in this work.

2.3.2 Site Data

As illustrated in the lower part of Figure 2, in order to determine the success or otherwise of a deployment, it was sometimes necessary to compare the operational duration of the deployment to the duration of suitable flow conditions on site (details of the procedure are given in Section 2.4). It was therefore necessary to access measured or modelled site data for many installation sites. This data was searched for in academic articles (again using the Web of Science [15]) and using the British Oceanographic Data Centre [21] and l'Institut Francais de Recherche Pour l'Exploitation de La Mer (Ifremer) [22] data repositories.

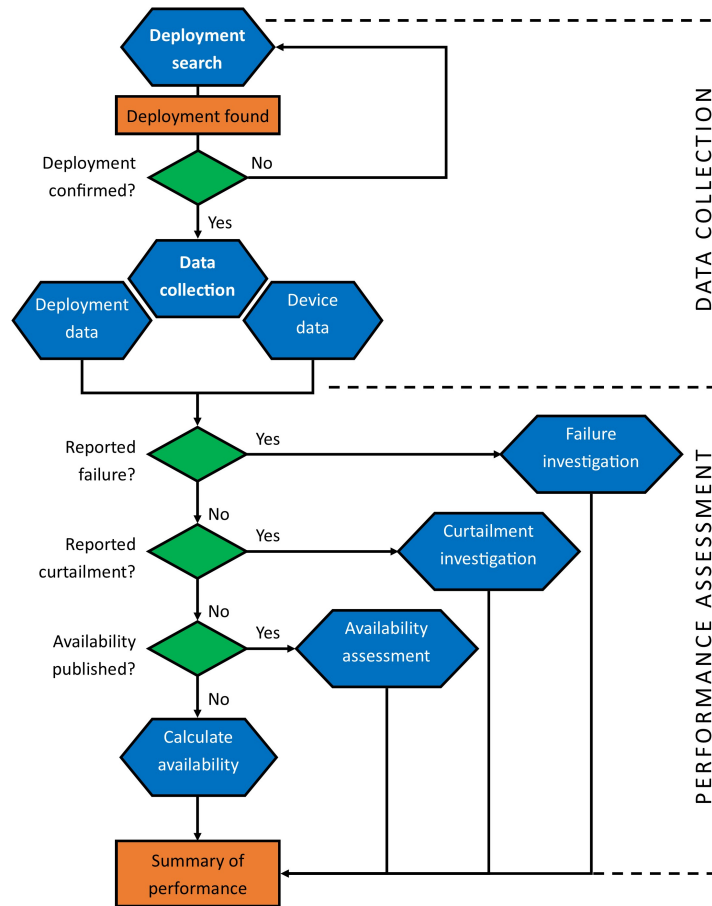


Figure 2: Conceptual image of the data collection and classification process

2.4 Deployment Performance

Deployment outcomes were classified into one of four categories, titled: ‘failed’, ‘curtailed’, ‘underperformed’, or ‘successful’. Classification was applied to both ongoing and historical deployments.

- Failed deployments were those where a part of the device or connection system under the control of the device developer suffered an unplanned outage, resulting in an aborted operation.
- A deployment was classed as curtailed if the intended deployment time was cut short or postponed in order to address a problem likely to lead to a failure, or if the same criteria were met due to maintenance or supply chain issues.
- An underperforming deployment was one where the system did not suffer a failure or curtailment, but did not meet a target for power generation, availability or deployment time. Where a target was specified prior to the deployment, results were compared to this target, otherwise site data was used to establish baseline figures to compare to published device data. This process is described in the following section.
- To class as successful, deployments were required to have met any specified targets for power generation, availability, or deployment duration. If no targets were specified, the deployment was deemed successful if there were no reported outages or unplanned breaks in power generation.

For deployments where no failure or curtailment was recorded, performance data was used to define whether a deployment had been successful or underperforming. A number of measures could be considered suitable for making this definition, and the measure used here was availability. Availability was used instead of other performance measures (such as capacity factor), as it gives a generic indication of reliability over a full deployment and is independent of device rated power, allowing it to be applied across devices over a range of sizes. Availability is used in the wind and tidal energy sectors to describe the potential for a device or farm of devices to generate electrical power. Two types of availability are commonly used [23]: ‘full-period’ availability and ‘in-limits’ availability. The former is defined as the ratio of hours during a given period when power is generated to the total number of hours in the period. The latter is the ratio of hours during a given period when power is generated to the total number of hours in the period when conditions allowed generation (i.e. when flow speeds were between cut-in and cut-out speeds). This second version (‘in-limits’ availability) was used in this study, since this is the approach adopted by tidal developers who have published data on availability.

Availability is defined here as A_v and is calculated as given in equation 1:

$$A_v = T_{gen}/T_{in-limits} \quad (1)$$

Where:

T_{gen} = the number of hours the device operated for during time period T

$T_{in-limits}$ = the number of hours during time period T where flow velocity was between device cut-in and device cut-out speeds

It is worth noting that whilst availability allows comparison between devices independent of rated power, devices with lower rated power are expected to have lower cut-in speeds, and would thus have a larger value of $T_{in-limits}$ compared to a device with higher rated power on the same site. This means that a lower rated power device would need to be more reliable in order to achieve the same availability. Similarly, to achieve the same availability, a device would have lower reliability requirements on a site with lower flow speeds than on a site with higher flow speeds, since the latter would have a greater proportion of hours below cut-in speed.

2.5 Site velocity data

For deployments which were not classed as failed or curtailed, and for which no published availability data could be obtained, availability was calculated from site and performance data wherever possible. Availability could be quantified when the number of hours of operation over a given total time period (T_{gen} above) was given. As a minimum, the calculation requires site flow velocity over one spring-neap cycle and device cut-in and cut-out speeds.

Information on the location of each deployment was gathered during the information gathering process described in Section 2.3 and Table 2. Deployment sites were classified based on their country. In countries where more than one deployment site was used, each was given a letter label. These labels are used here in preference to actual site locations, in order to preserve the anonymity of deployments (as discussed in Section 1.3). A total of 32 separate deployment sites around the world were identified. Flow velocity values over one spring-neap cycle were collected for each location from measured, modelled or estimated data as available, by applying the process described in Section 2.5.1. Since this flow data was only required for the calculation of deployment availability, it was ultimately redundant in cases where deployment availability was already published. However, flow data was collected for all sites before deployment classification was undertaken. This approach ensured the avoidance of any bias in the classification of deployment success.

2.5.1 Calculation of site velocity data

For some sites, flow velocity data was readily available from previous measurement campaigns. In other cases, modelled data was available. In cases where neither measured or modelled data could be obtained, estimated data was used. Estimates were made using data from the geographically nearest deployment site to the site for which data was required for which measured or modelled data was available. Data from the site with measured or modelled data was used at the site in question after applying a flow velocity scaling factor. Flow velocity values were scaled by multiplying by the ratio of the maximum spring tide velocity at the two sites. Cases where this process was undertaken are highlighted in the results. In total, measured data was available in 21 cases (5 sites), modelled data was available in 17 cases (9 sites) and estimated data was used in 20 cases (17 sites). Examples of measured, modelled and estimated site velocities over one spring-neap cycle for one deployment site are shown in Figure 3. This comparison is to illustrate the potential variation between the three sources of data, so all three types are shown. Note that in reality, values were not estimated if modelled data was available, and modelled data was only used if measured data was not available.

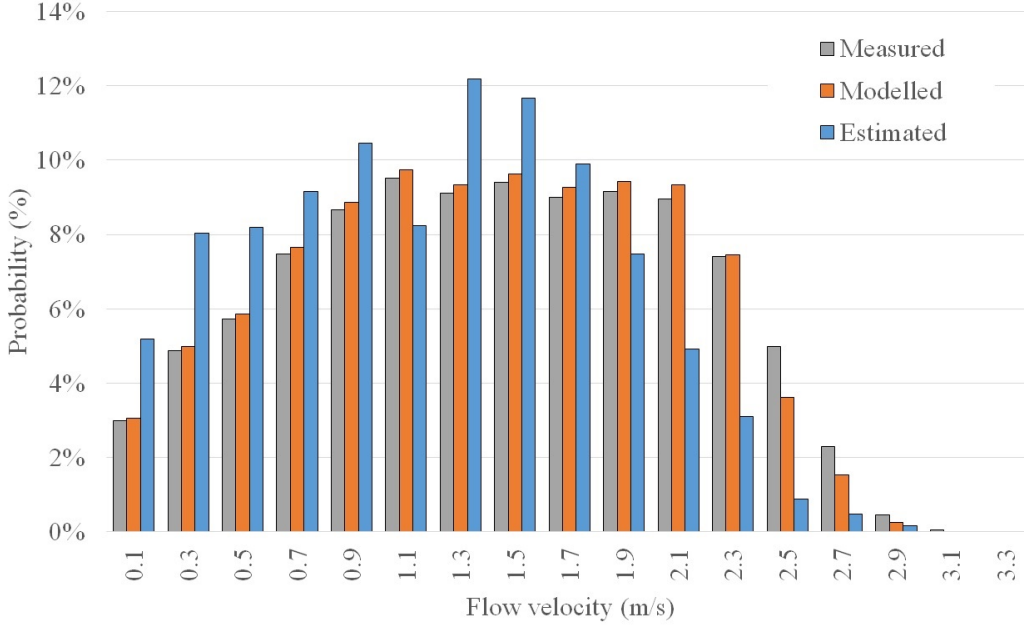


Figure 3: Statistical distribution of velocity over one spring-neap cycle for an example site: Measured, modelled and estimated as described above.

Figure 3 illustrates relatively small variation between measured and modelled data, with the modelled data matching measured values to within 4% in all cases up to 2.3m/s. Mean variation across the full data range is 5%. Estimated values, as would be expected, do not match the measured data so closely. Here maximum variation is of the order of $\pm 75\%$, though mean variation across the full range is again around 5% since the probability of lower velocities is overpredicted and the probability of higher velocities is underpredicted. This example data highlights that estimated data sets are less robust than modelled or measured data sets.

Each site at which deployments were recorded and the associated availability of modelled, measured or estimated site data is shown in Table 1. As noted, for some deployments availability data was published, so calculation using flow data was not required and hence the data referred to in Table 1 was not actually used. On sites with multiple deployments, availability data was available in some cases and not others, so the data referred to in Table 1 was only used in cases where availability was not published. Of the 39 deployments for which availability data was required to complete classification (i.e. those which were not classified as failed or curtailed), availability data was published directly for 8, and an additional three were described as not meeting availability targets, though data was not published. Availability was calculated for the remaining 28. Where availability data was published, if this data was given as full period availability it was converted to in-limits availability before use.

3 Results

At the time of this study, a total of 58 deployments were identified. The earliest deployments were recorded in 2003. The mean value of deployments per year was 3.2, with a peak of nine deployments in 2018. Geographically, most deployments were in Scotland (20), followed by France (10) and Canada (7). Deployments were also recorded in the Netherlands, China, Norway, England, Wales, Northern Ireland, Belgium, the USA, Australia and Denmark. In other countries, such as India, planned deployments were identified but no deployments appeared to have yet taken place [24]. Identified deployments by year and country of deployment are illustrated in Figure 5. Deployment classification is presented here without linking results to

specific deployments or locations, in order that industry-wide results can be considered instead of focussing on specific devices or locations. Deployment data was captured from a range of sources [25] - [51].

Table 1: Source of site data for deployment sites. (Num.=Number of deployments at site. Meas.=Measured velocity data, Mod.=Modelled, Est.=Estimated)

Country	Site	Num.	Velocity
Scotland	A	15	Meas.
	B	2	Mod.
	C	1	Meas.
	D	1	Mod.
	E	1	Est.
France	A	3	Mod.
	B	2	Mod.
	C	2	Mod.
	D	1	Meas.
	E	1	Est.
	F	1	Est.
Canada	A	3	Mod.
	B	2	Meas.
	C	2	Mod.
Netherlands	A	2	Est.
	B	1	Est.
	C	1	Est.
China	A	2	Est.
	B	1	Est.
England	A	2	Est.
	B	1	Est.
Norway	A	1	Est.
	B	1	Est.
Wales	A	1	Est.
	B	1	Mod.
USA	A	1	Est.
	B	1	Mod.
N. Ireland	-	2	Meas.
Belgium	-	1	Est.
Australia	-	1	Est.
Denmark	-	1	Est.

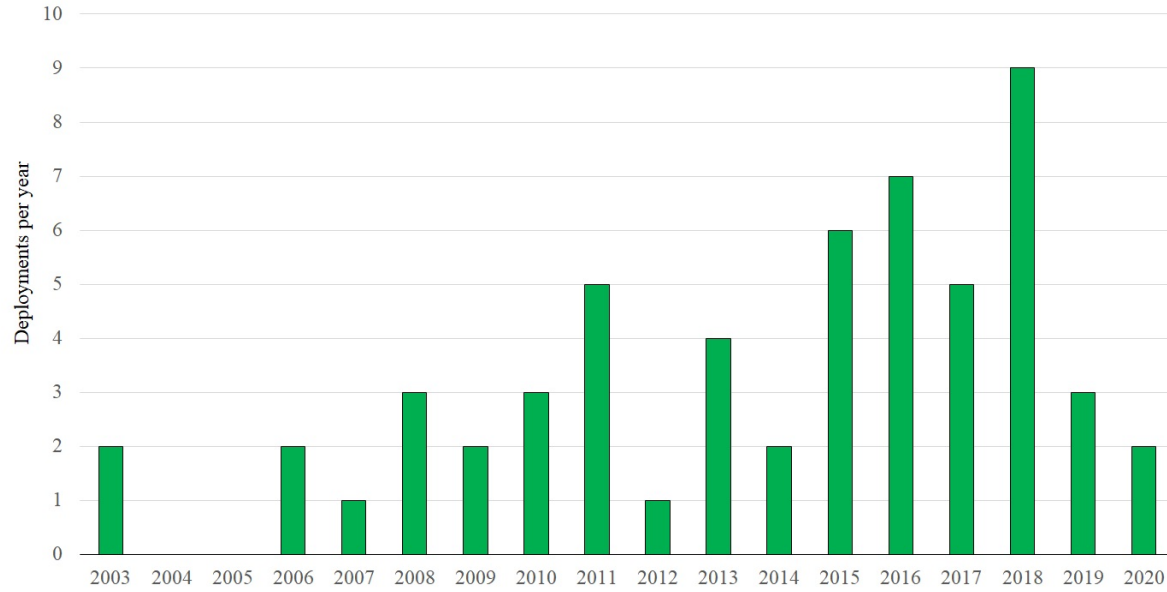


Figure 4: Identified deployments by year of deployment.

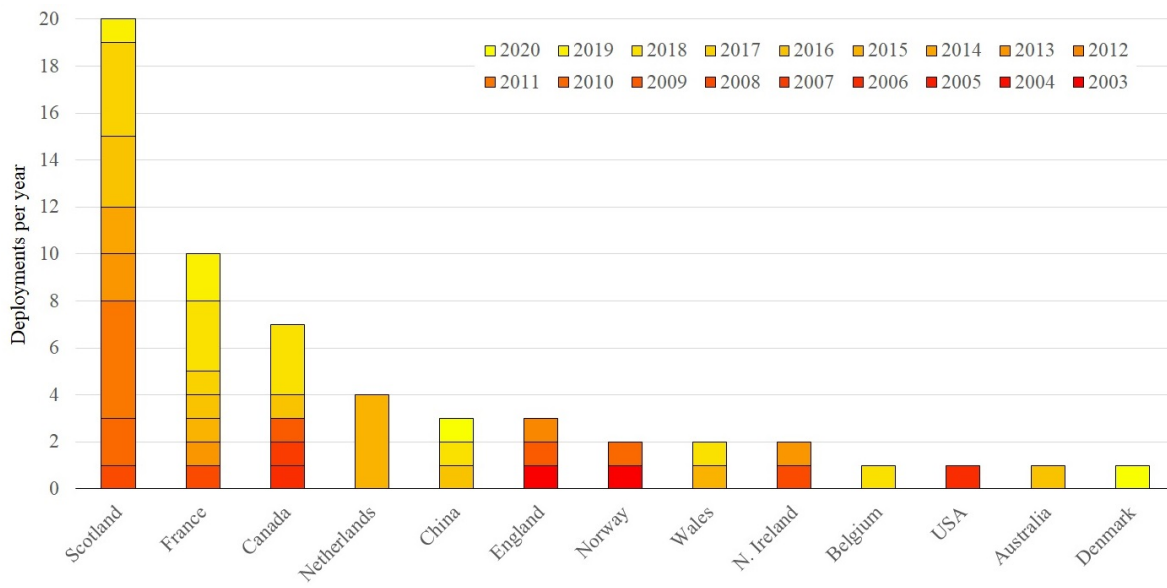


Figure 5: Identified deployments by year and country of deployment. Darker shading and red colour indicates deployments earlier in the 2003-2020 period.

3.1 Descriptive statistics

Of the 58 deployments undertaken, the majority (46, 79%) were of single devices. There were six deployments of two devices (11%) and six deployments (11%) of three or more devices.

50 deployments were of horizontal axis turbines (86%), 3 were vertical axis turbines (9%), and the remaining 5 were oscillators (9%).

The majority of devices (46 deployments, 79%) were not ducted.

10 deployments were of sub-100kW rated power devices (18%), 26 were of devices in the 100kW to 1MW range (45%), and 21 devices were of 1MW or larger (38%). In one case it was not possible to ascertain the rated power of the device.

20 deployments were not grid connected (36%). Two devices were connected to small local grids (4%), and the remaining 35 (61%) of devices were connected to a mainland grid. In one case it was not possible to ascertain whether a grid connection had been used.

The most common foundation type was seabed fixed (40 deployments, 70%). Of these, 14 deployments (35%) used piled foundations, 25 (63%) used gravity base foundations, and the remaining 2 (5%) were based on fixed pontoons. All 17 deployments of the floating foundation type used a moored system. A relationship can be observed between device type and foundation type, with all vertical axis devices employing a floating moored foundation system, though due to the smaller number of vertical axis device deployments, this accounts for only 18% of total floating moored deployments. No vertical axis deployments used piled, pontoon or gravity base foundations. Horizontal axis devices and oscillators share similar distributions of foundation types: 27% and 20% respectively of each device type use the floating moored, 24% and 20% fixed piled and 45% and 60% fixed gravity bases. The only two fixed pontoon mounted structures were horizontal axis turbines (4% of this type of deployment used this foundation type).

3.1.1 Temporal trends

Trends over time illustrate increasing numbers of deployments, and an increasing number of deployments of devices with higher rated power. The first deployment of a device with rated power of over 1MW took place in 2008; since then there have been deployments of this size every year. This data is illustrated in 6. Similarly, arrays of multiple devices have become more common since the first multi-device deployment in 2006. This data can be seen in the summary data table in Section 5.

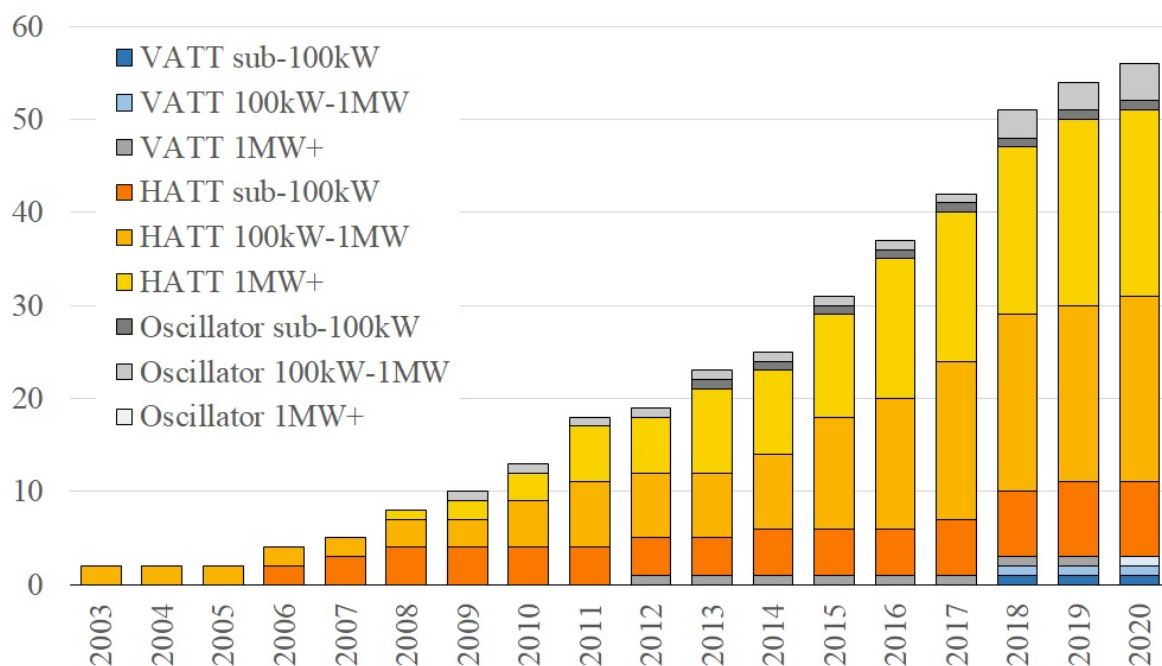


Figure 6: Growth in devices with higher rated power. Colour indicates device type, shading indicates rated power.

3.2 Deployment classification

Based on the criteria described in Section 2.4, deployments were classified as ‘failed’, ‘curtailed’, ‘underperforming’ or ‘successful’. Deployment results are given in Figure 8. Full results for all deployments are given in Table 5. Of the 58 deployments captured in this study, over half (32 deployments, 54%) were successful, ten (18%) were classed as having failed, eight (14%) as curtailed, and eight (14%) as underperforming. 19 deployments (33%) were ongoing at the point of data capture. These deployments were classified based on their performance to date. Of these ongoing deployments, 14 (73%) were successful, two (11%) underperforming, one (5%) curtailed and two (11%) failed. In both cases where ongoing deployments were classified as failed, the failure occurred during or soon after installation, and was subsequently repaired.

The relationships between deployment status and device type, rated power, grid connection, foundation type and year of deployment are explored in the following sections.

3.3 Unsuccessful deployments

The proportion of unsuccessful deployments which fell into each of the three categories introduced in Section 2.4 are discussed in the following subsections and figures.

3.3.1 Failures

The specific causes of the ten deployments classified as failed fall into four categories, as described below. Note that two failures fell into multiple categories, so are counted more than once.

- Blade failure: Four cases.
Blades failed mechanically, either during the early stages of the deployment or (in one case) after deployment but before operation.
- Generator: Three cases.
The generator failed or sustained damage which rendered it unable to operate, either by overheating or internal component failure.
- Monitoring: Three cases.
Monitoring systems required in order to meet the operation license failed, meaning the turbine could no longer be allowed to operate.

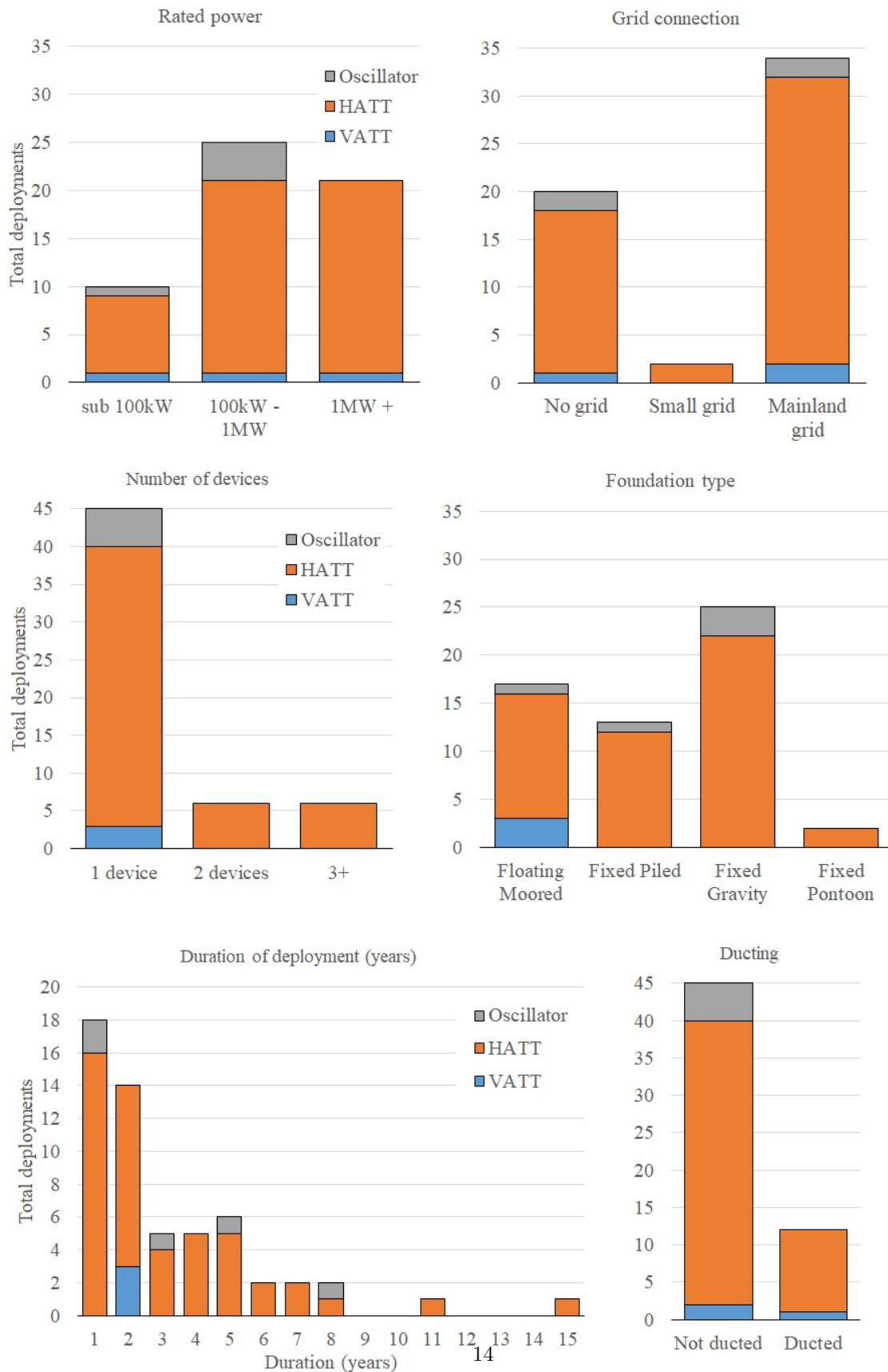


Figure 7: Descriptive statistics for deployments reported in this study. Top l-r: Rated power, grid connection, Middle l-r: Number of devices, foundation type, Bottom l-r: Duration of deployment, ducting. Colour indicates device type.

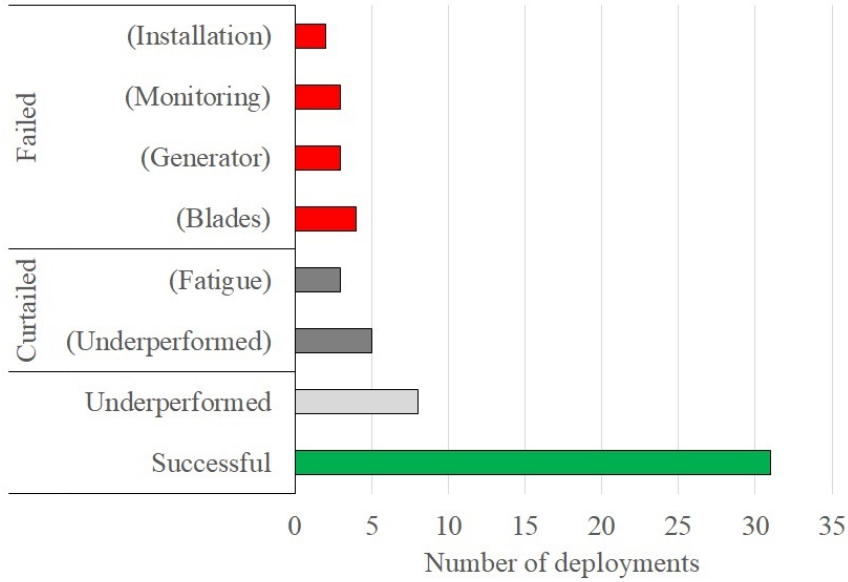


Figure 8: Deployment outcome results by category and subcategory.

- Installation: Two cases.
Turbine or support structure components were damaged during installation, meaning the installation could not continue.

3.3.2 Curtailments

The eight deployments classified as curtailed fell into two categories:

- Underperformance: Five cases.
Five deployments were withdrawn from service earlier than intended due to underperformance relative to their expected output. These were classed as curtailed deployments rather than underperforming deployments, as they ended earlier than intended. In some cases, the curtailment was attributed directly to the deployment not meeting the required power output targets, whereas in others the lower-than-expected performance led to the suspension of testing or the liquidation of the operating company.
- Fatigue: Three cases.
Three deployments were curtailed due to fatigue of either the support structure, mooring equipment, or corrosion of components. It is assumed that these deployments would have failed had they not been curtailed.

3.4 Performance results

Deployments which were not classified as failed or curtailed were classified as either successful or underperforming. To class as successful, deployments were required to have met any targets for power generation, availability, or deployment duration set by the developer. If no targets were specified,

ed, the deployment was deemed successful if there were no reported outages. Consequently, the underperforming / successful threshold was defined independently for each deployment.

4 Discussion

4.1 Causes of failure

A primary aim of this work is to highlight the most common modes of failure and identify any relationships between failure type and deployment characteristics. Here a collection of results are illustrated, in order to explore the relationships between deployment type and outcome, and to allow empirical observations to be made, seeking to derisk future projects.

Ducting

In total, 12 deployments were of ducted devices, and 43 were not ducted. A greater proportion of failures occurred in ducted devices (25% of ducted devices failed, whereas 13% of non-ducted devices failed). It is notable that all but one of these failures occurred early in the time period considered (before 2009), which may suggest a relationship between year of deployment and success. This may be expected due to the high failure rate of the early industry, but it is notable that even when considering only deployments before 2010, 75% of deployments using ducted devices failed, whereas only 33% of those using non-ducted devices failed, possibly suggesting that higher flow rates achieved through ducting increase turbine loading.

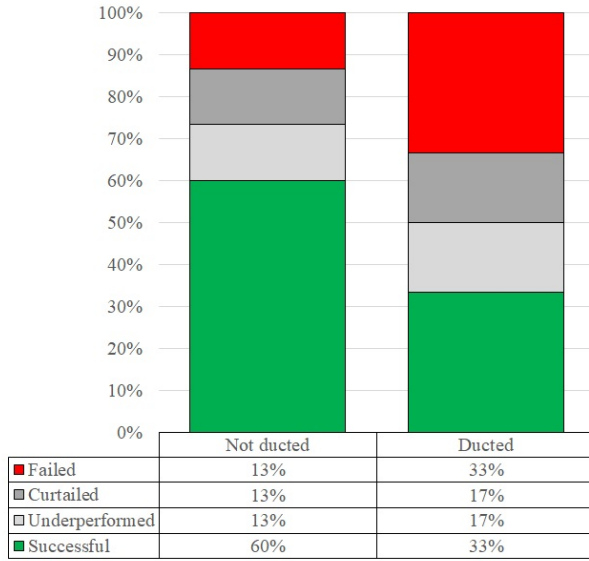


Figure 9: Deployment outcome statistics vs ducting

Extractor type

The overall most common cause of device failure was mechanical blade failure. This type of failure occurred only in horizontal axis devices, and occurred in 6% of all deployments of this type. These failures occurred across the full range of device rated power, across all grid connection types, and in both ducted and non-ducted configurations. Blades appear to be a particular weakness in the reliability of tidal turbine deployments, particularly in horizontal axis devices. With only three and five deployments respectively, it is not possible to draw a firm conclusion as to whether VATT and Oscillator deployments are more or less susceptible to blade failures. Only limited detail is available, but in three of the four failures attributed to turbine blades, the failure can be attributed to the underprediction of in-use blade loading during the design process, i.e. the blades failed because their design specification was incorrect. The industry is well aware of this challenge, and the understanding of these loads as well as blade testing and monitoring are areas of ongoing work [52] [53].

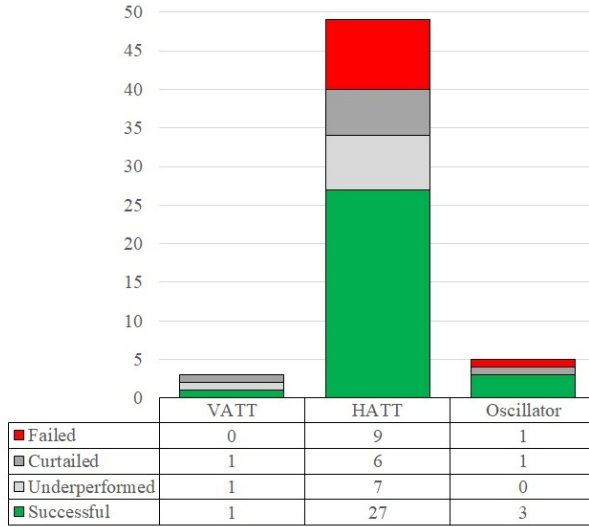


Figure 10: Deployment outcome statistics vs extractor type

Mounting & foundation type

All deployments which failed were installed on fixed foundations. This suggests that floating foundations may be linked to a lower failure rate. However, floating foundation deployments showed a significant number of curtailments (curtailment and failure rates were 29% and 0% respectively for floating foundations, and 10% and 25% respectively for fixed foundations). This may suggest that the potential for easier recovery of a floating foundation device leads to an increased likelihood of intervention before failure, resulting in more curtailments but fewer failures.

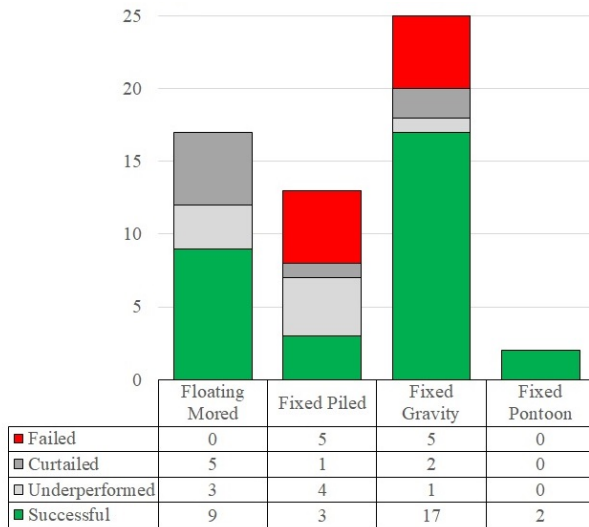


Figure 11: Deployment outcome statistics vs mounting and foundation type

Device rated power

Deployments of low rated power devices tended to occur early in the time period considered. These deployments were often undertaken in the interests of research rather than power generation. Consequently, many of these early deployments had low power generation or availability targets. This resulted in no deployments

of devices in the sub 100kW being classified as underperforming. Aside from this, broadly similar proportions of each outcome category are seen across the three device rated power categories.

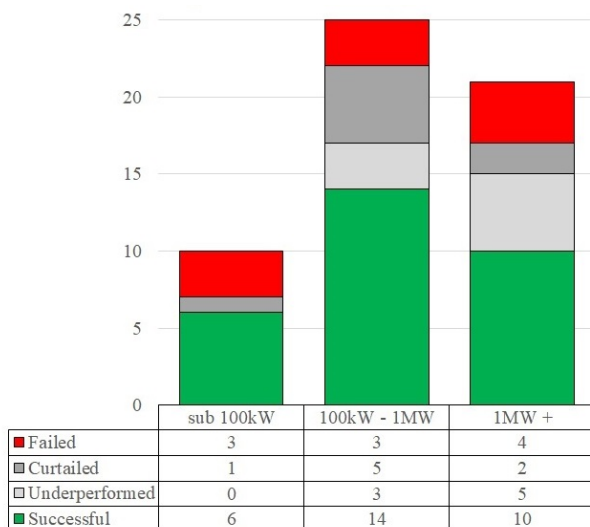


Figure 12: Deployment outcome statistics vs device rated power

Number of devices

Failure numbers appeared to be independent of the number of devices included in a deployment, with all three cases recording failures in around 17% of deployments. Similarly, total numbers of unsuccessful (i.e. failed, curtailed or underperforming) deployments were similar regardless of the number of devices in a deployment.

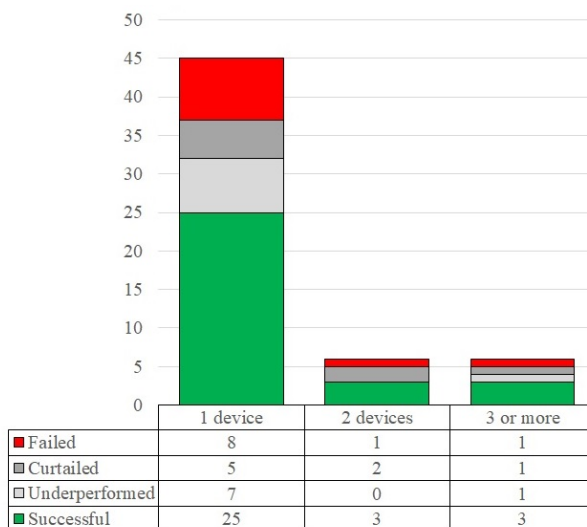


Figure 13: Deployment outcome statistics vs number of devices

Grid connection

Grid connection appeared to have only limited impact on the likelihood of deployment success, with 17.6% of deployments connected to mainland grids failing, in comparison to 20% of deployments which were not grid

connected. This small difference may be attributable to the tendency for early stage research devices to be off-grid, while grid-connected devices may have undergone more prior testing and development. Nonetheless, the difference in failures is small, and the volume of data does not permit full conclusions. Only two deployments used small grids (both on islands), meaning there is insufficient data to draw meaningful conclusions in this case.

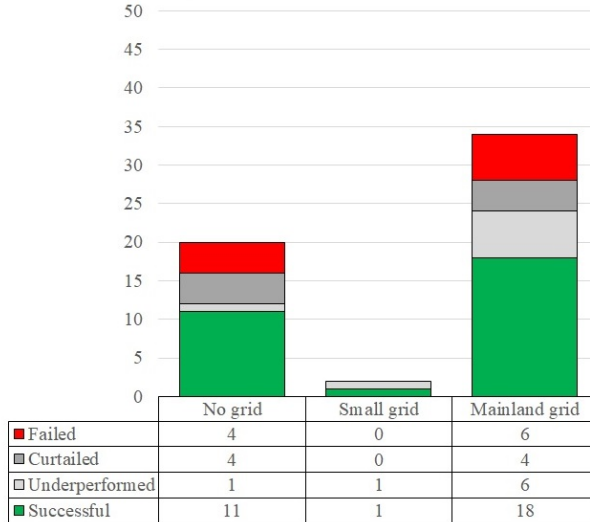


Figure 14: Deployment outcome statistics vs grid connection

Location

Deployments were reported in thirteen countries, however the number of deployments was low in most cases. Only three locations (Scotland, France and Canada) were found to have more than four deployments. Of the three countries with more than four deployments (Canada: 7, France: 10, Scotland: 20), Canada was found to have the greatest proportion of failures. 57% of devices deployed in Canadian waters failed, and another 28% were either curtailed or underperformed. The common feature of locations where a large number of devices were found to fail may be flow conditions. Figure 15 illustrates the proportion of failures recorded at sites compared to maximum spring tide flow velocity, shown in 0.5m/s steps from 1m/s to 4.5m/s. There is a trend for higher failure proportion at higher flow rates. These high flow rates appear to increase the likelihood of all types of failures. It is not clear at present whether any more specific relationships may occur between flow conditions (such as turbulence levels for example) and failure likelihood, or whether the strongest relationship is with flow velocity. There is insufficient data in this study to consider these potential relationships.

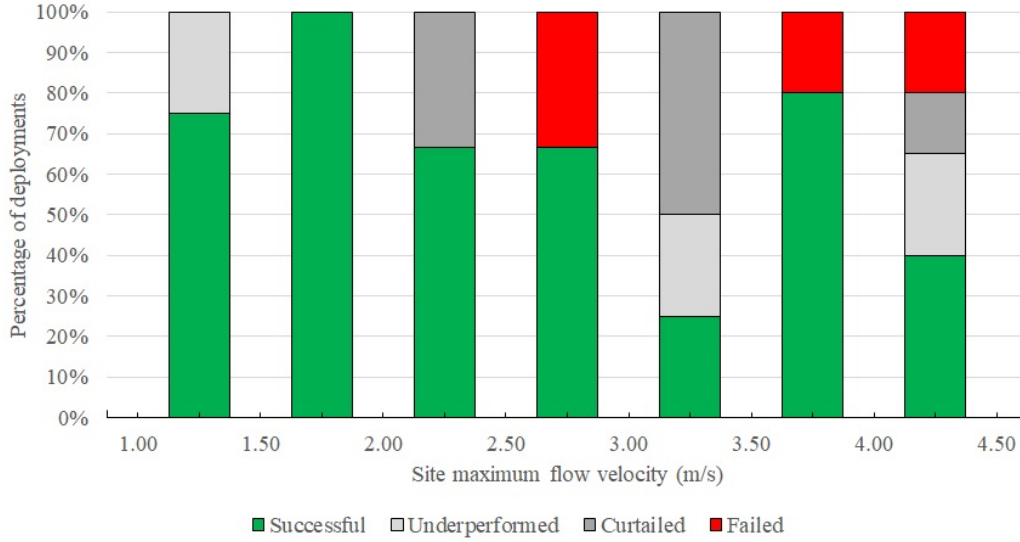


Figure 15: Deployment outcome statistics vs peak flow speed at deployment location

Year of deployment

In general, likelihood of failure appears to fall over time. Considering the proportion of failures per year, the total number of failures, and the time between failures, the captured data suggests that the industry has reduced likelihood of failure between 2003 and 2020. This temporal trend for increased reliability will be discussed in more detail in the following sections.

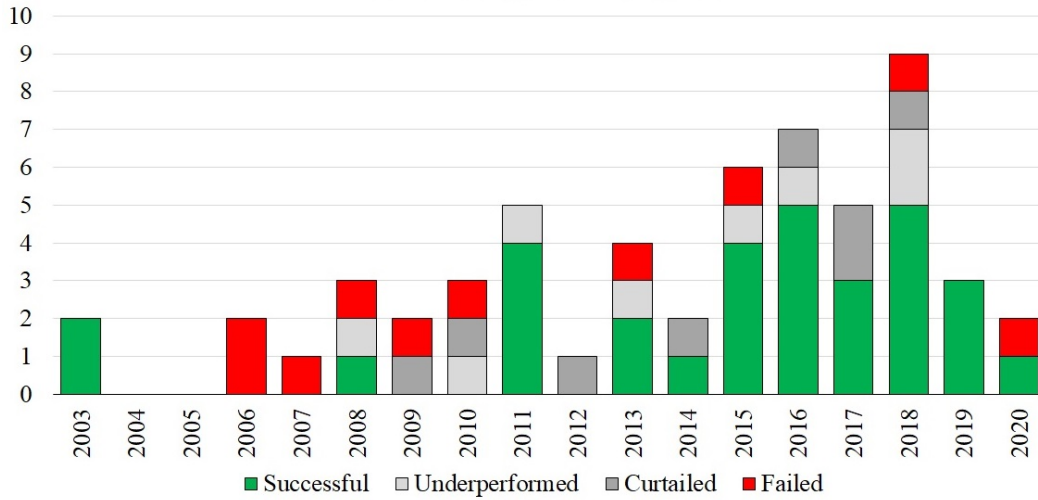


Figure 16: Deployment outcome statistics vs year of deployment

4.2 Reliability growth

The total deployment duration of tidal stream energy deployments highlighted in this study is 1,359,994 hours (approximately 155 years of total deployment time). Of this, the majority (1,175,304 hours or approximately 134 years) was completed by horizontal axis devices. 137,970 hours (16 years) were completed by oscillating devices, and 46,720 hours (5 years) by vertical axis devices. As highlighted in the work of Duane [11],

reliability for engineering systems can be expected to improve with cumulative deployment duration, i.e. engineering and operating experience of the systems. Figure 17 illustrates the change in number of failures to date with cumulative duration of deployment for horizontal axis, vertical axis and oscillating devices, and for the tidal stream energy industry as a whole. Failures are illustrated as a percentage of deployments (i.e. the percentage of deployments which were classified as having failed), and only failed or curtailed deployments were included (i.e. not those classified as underperforming).

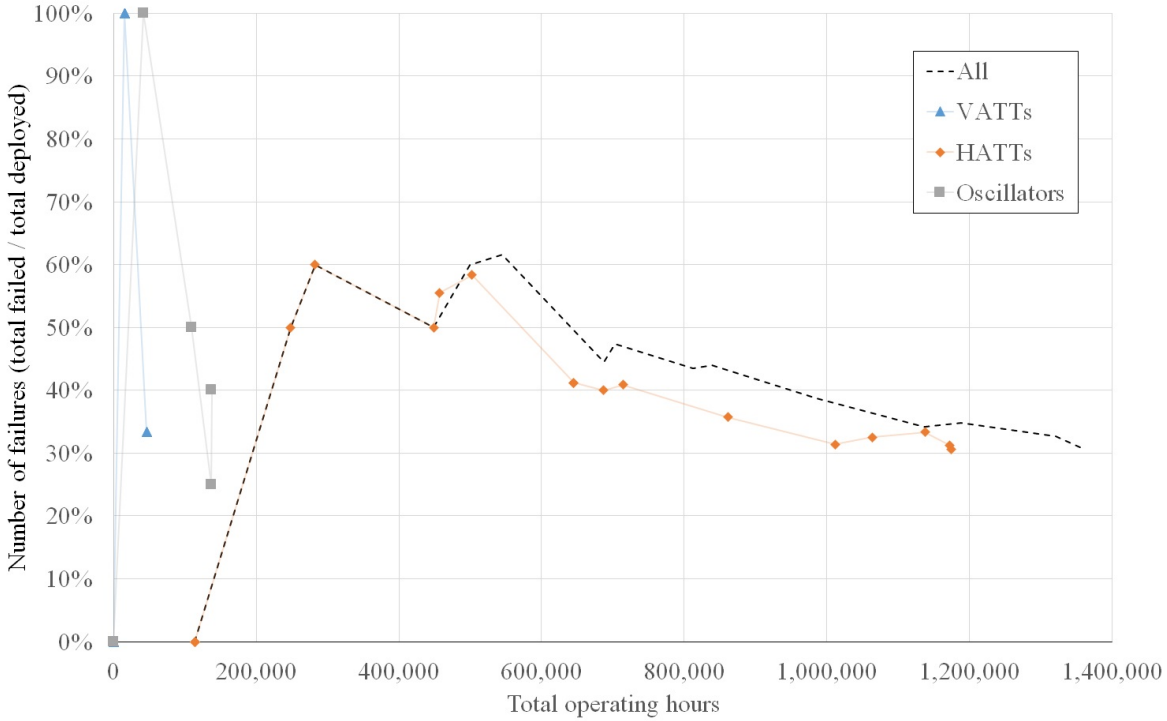


Figure 17: Reliability growth illustrated by failure rates of HATTs, VATTs, Oscillators and all tidal stream energy devices vs cumulative duration of deployment

Figure 17 illustrates that in terms of total deployment duration, horizontal axis turbines dominate the market, with a cumulative deployment duration over 25 times longer than that of vertical axis turbines, and over eight times longer than that of oscillating devices. Due to the low volumes of deployments, both VATT and oscillating devices experienced periods where the cumulative deployment failure rate was 100%, i.e. that all deployed devices up to that point had failed. At the time of writing, cumulative failure rates for VATTs and oscillators are 33% and 40% respectively. Horizontal axis devices are the key contributor to the total cumulative operating hours for tidal stream energy devices. The general trend shows HATT (and overall) failures falling over time, after peaking at over 60% in both cases. As of August 2020, cumulative failure rates for horizontal axis devices are now around 31%, and for all tidal stream energy devices around 32%. The similarity in these figures is another indicator of the major contribution made to the overall deployment duration by HATT devices.

4.2.1 Learning rate

The data presented in Figure 17 also allows the calculation of learning rate. Taking the sector total proportion of failures at 600,000 operating hours (55%) and at 1,200,000 operating hours (35%) suggests a reliability improvement of 36% with the doubling of operational hours from 600,000 to 1,200,000 hours. Estimates suggest that O&M accounts for of the order of 30% to overall project cost. On this basis, a 36% improvement

in reliability would lead to a total learning rate of 10.9%. This appears to support the 10% learning rate estimated by the Carbon Trust [10].

4.2.2 Comparison with wind energy

These reliability figures compare unfavourably with current onshore and offshore wind turbine reliability. In these devices, a recent study of a population of turbines gave failure rates of between 0.5 and 2.1 failures per year [54] (the sum of failures in categories ‘Major replacement’ and ‘Major repair’ over an 8 year period for a population of 350 turbines), giving a mean annual percentage failure rate of 0.37%. However, this population alone accounts for around 15.5 million operating hours, which is of the order of 10 times more than the total cumulative operating hours in the tidal industry. A crude calculation taking into account total global wind power capacity [55], capacity factor [56] and average turbine size [57] is illustrated in Table 2 and suggests that the wind industry has amassed over 1 billion operating hours to date, and exceeded 1.5 million hours (the current total for tidal stream energy) before 1996.

Table 2: Estimation of global cumulative wind turbine operating hours, based on total global capacity, most common turbine power rating and mean annual capacity factor.

Year	Capacity (GW)	Cf (%)	Power (MW)	Time (1000s hrs)
1996	6	6	1.2	2,628
1997	8	7	1.4	6,132
1998	10	8	1.6	10,512
1999	13	9	1.8	16,206
2000	17	10	2	23,652
2001	24	11	2.4	33,288
2002	31	12	2.8	44,926
2003	39	13	3.2	58,805
2004	47	14	3.6	74,816
2005	59	15	4	94,198
2006	74	16	4.6	116,745
2007	94	17	5.2	143,665
2008	120	18	5.8	176,289
2009	159	19	6.4	217,639
2010	198	20	7	267,195
2011	238	21	7.4	326,361
2012	282	22	7.8	396,037
2013	318	23	8.2	474,171
2014	369	24	8.6	564,379
2015	432	25	9	669,499
2016	487	26	9.75	783,262
2017	539	27	10.5	904,676
2018	591	28	11.25	1,033,530
2019	651	29	12	1,171,346

Reliability data from the very young wind turbine industry is not widely available, but Tavner [58] quotes wind turbine failure data from two German sources and one Danish source, beginning in late 1995. This data shows a range between 0.8 and 3.0 failures per turbine per year for the year 1996. This includes minor failures and major failures. Considering only major failures, since only major failures have been considered in the tidal turbine data and using the distribution of failure types given in [54], these figures suggest that the wind industry may have experienced between 0.025 and 0.09 major failures per turbine during 1996.

This gives a useful benchmark, since the 1996 wind turbine industry, in terms of accumulated operating hours, is the closest approximation to the current position of the tidal stream energy industry for which reliability data is available (the 1996 wind industry had accumulated approximately 2.6 million operating hours, whereas to August 2020 the tidal stream energy industry had accumulated approximately 1.4 million operating hours).

Based on the data collected in the present study, the failure rate of the tidal stream energy industry as a whole is around 0.065 major failures per turbine per year. This suggests that the industry may be following a similar trajectory to the wind energy industry, though further timely assessment would be needed to confirm this.

4.3 Limitations

It should be noted that this work considered the relationship between failure and only ‘top level’ deployment and device characteristics. Much more detailed, device and technology specific reliability assessments could be considered, for example blade materials and construction type, foundation design details, or site characteristics such as ebb and flow offset angle or (as mentioned in Section 4.1) turbulence intensity. The top level data used here means it has not been possible to determine secondary causes of failures, and all of these studies will require detailed design and environmental data, so will need to be carried out for individual technologies and sites. The continued analysis of failures and sharing of success will help improve reliability, and ultimately contribute to source of energy which is sustainable in both environmental and economic terms. In cases where deployments did not fail and were not curtailed, if availability data was not available, flow velocity data was used to calculate availability. If measured or modelled flow data was not available, estimated data was used. This estimated data is of limited accuracy, and may impact the reliability of the resulting availability data. However, availability was calculated using estimated flow velocity data in only one case. Availability was calculated from flow data in eight of the 58 deployment cases considered, using measured data in five cases, modelled data in two cases, and estimated data in one case.

4.3.1 Marine life interaction

Environmental factors such as interaction with marine life are another potential contributor to unsuccessful performance. Monitoring of marine life interaction has been undertaken at many deployments and suggests that collision risk is low due to avoidance, but clearly this risk should be minimised. The inclusion of environmental factors in performance results would be a logical next step in this work.

4.3.2 Statistical assessment

Due to the relatively small number of tidal stream energy deployments, the dataset on which statistical analysis described here has been undertaken is unavoidably limited. In some categories, particularly VATTs and Oscillators, the number of deployments is sufficiently small that individual deployments have a significant impact on the total statistics. As the industry continues to grow and more data is available, it will be possible to study statistical trends with greater accuracy and in greater detail.

5 Conclusions

This work aimed to identify and classify the status and performance of all previous deployments of tidal stream energy converters, in order to highlight the most common modes of failure and identify any relationships between failure type and location, device type or design, or other project features. The work also aimed to study the impact of the diversity of device designs on reliability and reliability growth.

58 deployments were identified between 2003 and August 2020. Of these, the majority were deployments of single horizontal axis turbine devices, most commonly not ducted, between 100kW and 1MW in rated power, grid connected, and mounted on foundations fixed to the seabed.

The most prevalent failure mode across all deployments was blade failure. This, in common with failures due to generator failure, monitoring failure and installation failure, appears to be independent of most deployment characteristics. The strongest relationship between failure and deployment characteristic was with foundation type, where devices with a floating foundation system did not experience any failures, despite making up 30% of total deployments. This type of foundation system did experience a significant number of curtailments, perhaps suggesting a tendency for floating devices to be removed before failure, since this can take place more easily than in the case of a fixed device.

The only other turbine characteristic which showed a relationship with failure likelihood was ducting, with ducted devices more likely to fail than non-ducted devices. Temporally, devices deployed earlier in the timeline were more likely to fail, and failures were found to be more likely in sites with high flow velocity, with deployments in Canada having a particularly strong relationship with failure.

The most prevalent cause of curtailment was underperformance, whereby deployments were withdrawn from service because they did not deliver the expected power output. This type of curtailment was most common in grid-connected deployments towards the end of the time period considered, but occurred across all deployment types and sizes. This is in part likely to be due to the increase in power generation targets as technology has developed.

The tidal stream energy sector has so far accumulated around 1.4 million operating hours. The majority of these have been completed by horizontal axis devices. Failure likelihood has fallen across all types of tidal stream energy device, but is lowest in horizontal axis devices. In comparison to established technologies like wind energy, 1.4 million hours is a very low figure (the wind energy industry to date has achieved over 1 billion hours). The likelihood of failure in a tidal stream turbine deployment at the time of writing is similar to that of a wind turbine in 1996, when the wind industry had achieved 2.6 million operating hours. This is a positive result, and appears to suggest that tidal stream energy is following a similar reliability growth curve and that failure likelihood will continue to fall as more deployments are completed.

Acknowledgements

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Appendix A: Deployment classification data table

A full summary table of data on the deployments included in this work is given below. In each case the major features of the deployment are given as well as the final status, and the source of the status, described as follows:

Lit. - Status ascertained from literature

Rep* - Status reported by developer

Rep[†] - Status ascertained from availability reported by developer

Calc* - Status ascertained from availability calculated from measured flow velocity

Calc[†] - Status ascertained from availability calculated from modelled flow velocity

Calc[‡] - Status ascertained from availability calculated from estimated flow velocity

Start	End	Country	Site	Devices	Rated power	Grid	Foundation	Mooring	Status	Av	Source
2018	Ongoing	France	D	1	<100kW	Main grid	Floating	Moored	S		Rep [*]
2015	2016	France	B	1	≥1MW	Local grid	Fixed	Gravity	S		Rep [*]
2018	2019	France	B	1	≥1MW	Local grid	Fixed	Gravity	U	0.25	Rep [*]
2019	Ongoing	Scotland	A	1	≥1MW	Main grid	Floating	Moored	S		Rep [*]
2018	Ongoing	Wales	A	1	≥100kW, <1MW	Off grid	Fixed	Gravity	S	0.77	Rep [†]
2018	Ongoing	Belgium	-	1	≥100kW, <1MW	Off grid	Floating	Moored	U	0.33	Rep [†]
2018	Ongoing	Canada	C	2	≥100kW, <1MW	Off grid	Floating	Moored	C		Lit.
2018	2019	Canada	C	1	≥100kW, <1MW		Floating	Moored	S		Rep [*]
2016	Ongoing	China	A	2	≥100kW, <1MW	Main grid	Fixed	Pontoon	S	0.35	Rep [*]
2018	Ongoing	China	A	1	≥100kW, <1MW	Main grid	Fixed	Pontoon	S	0.35	Rep [*]
2016	2017	Canada	A	1	≥1MW	Main grid	Fixed	Piled	U		Rep [*]
2018	Ongoing	Canada	A	1	≥1MW	Main grid	Fixed	Piled	F		Lit.
2009	2010	Canada	A	1	≥1MW	Off grid	Fixed	Gravity	F		Lit.
2015	2016	Wales	B	1	≥100kW, <1MW	Main grid	Fixed	Gravity	F		Lit.
2016	Ongoing	Scotland	F	3+	≥100kW, <1MW	Main grid	Fixed	Gravity	S	0.94	Calc [*]
2013	2014	France	A	1	≥1MW	Off grid	Fixed	Gravity	S	0.87	Calc [†]
2016	2017	France	A	2	≥1MW	Off grid	Fixed	Gravity	C		Lit.
2019	Ongoing	France	A	1	≥1MW	Main grid	Fixed	Gravity	S	0.91	Rep [†]
2020	Ongoing	China	B	1	≥100kW, <1MW	Main grid	Fixed	Piled	S		Rep [*]
2017	2017	France	C	1	<100kW	Off grid	Fixed	Gravity	S		Rep [*]
2019	Ongoing	France	E	1	<100kW	Main grid	Fixed	Gravity	S		Rep [*]
2018	2019	France	C	1	<100kW	Off grid	Fixed	Gravity	S		Rep [*]
2008	2009	France	F	1	<100kW	Off grid	Fixed	Gravity	S		Rep [*]
2008	2015	Scotland	A	1	≥1MW	Main grid	Fixed	Piled	U	0.43	Calc [*]
2010	2013	Scotland	A	1	≥100kW, <1MW	Main grid	Fixed	Piled	U	0.05	Calc [*]
2010	2010	Scotland	A	1	≥1MW	Off grid	Fixed	Gravity	F		Lit.
2011	2016	Scotland	A	1	≥1MW	Main grid	Fixed	Gravity	S		Rep [*]
2011	2018	Scotland	A	1	≥1MW	Main grid	Fixed	Gravity	S		Rep [*]
2011	2015	Scotland	A	1	≥1MW	Main grid	Fixed	Gravity	S	0.98	Rep [†]
2011	2013	Scotland	A	1	≥100kW, <1MW	Main grid	Floating	Moored	U	0.31	Rep [†]
2013	2016	Scotland	A	1	≥1MW	Main grid	Fixed	Piled	U	0.17	Rep [†]
2013	2015	Scotland	A	1	≥1MW	Main grid	Fixed	Piled	F		Lit.
2016	2018	Scotland	A	1	≥1MW	Main grid	Floating	Moored	S	0.76	Calc [*]
2013	Ongoing	N. Ireland	-	1	<100kW	Off grid	Fixed	Gravity	S		Rep [*]
2015	Ongoing	Netherlands	B	3+	≥1MW	Main grid	Floating	Moored	U		Rep [*]
2015	Ongoing	Netherlands	C	3+	≥100kW, <1MW	Main grid	Floating	Moored	S		Rep [*]
2015	2015	Netherlands	A	1	≥100kW, <1MW	Main grid	Floating	Moored	S		Rep [*]
2015	Ongoing	Netherlands	A	1	≥100kW, <1MW	Main grid	Floating	Moored	S		Rep [*]
2017	2017	Scotland	A	1	≥100kW, <1MW	Main grid	Floating	Moored	C		Lit.
2008	2019	N. Ireland	-	2	≥100kW, <1MW	Main grid	Fixed	Piled	F		Lit.
2003	2009	England	B	1	≥100kW, <1MW	Off grid	Fixed	Piled	S		Calc [†]
2012	2014	England	A	1	≥1MW	Main grid	Floating	Moored	C		Rep [*]
2011	2012	Scotland	A	2	≥100kW, <1MW	Off grid	Fixed	Piled	S		Rep [*]
2009	2014	England	A	1	≥100kW, <1MW	Main grid	Fixed	Piled	C		Rep [*]
2006	2007	Canada	B	1	<100kW	Off grid	Fixed	Piled	F		Lit.
2007	2011	Canada	B	1	<100kW	Off grid	Fixed	Piled	F		Lit.
2016	2017	Australia	-	1		Off grid	Floating	Moored	S		Rep [*]
2003	2011	Norway	A	1	≥100kW, <1MW	Main grid	Fixed	Gravity	S	0.98	Calc [†]
2017	Ongoing	Scotland	C	1	≥1MW	Main grid	Fixed	Gravity	S	0.94	Rep [†]
2016	Ongoing	Scotland	C	3+	≥1MW	Main grid	Fixed	Gravity	S	0.94	Rep [†]
2010	2012	Norway	B	3+	≥100kW, <1MW	Off grid	Floating	Moored	C		Rep [*]
2017	2018	Scotland	D	2	≥100kW, <1MW	Off grid	Floating	Moored	S	0.79	Calc [*]
2014	2017	Scotland	E	1	<100kW	Off grid	Floating	Moored	C		Rep [*]
2006	Ongoing	USA	-	3+	<100kW	Main grid	Fixed	Gravity	F		Lit.
2020	Ongoing	Denmark	-	1	≥100kW, <1MW	Main grid	Fixed	Gravity	F		Lit.
2014	2014	Scotland	A	1	≥100kW, <1MW	Off grid	Fixed	Gravity	S	0.85	Rep [†]
2017	2018	Scotland	A	1	≥100kW, <1MW	Main grid	Fixed	Gravity	C		Lit.
2012	2013	USA	A	1	≥100kW, <1MW	Main grid	Fixed	Piled	S		Rep [*]

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