Failure and reliability growth in tidal stream turbine deployments

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Abstract—**Many technical challenges have been addressed since the first commercial deployment of a tidal stream turbine in 2003. However, the technology is not yet competitive with other renewable energy generation in cost of energy terms, and there remains a reluctance among investors due to the perceived risk of device failure. In this work we reviewed and categorised all available tidal stream energy deployment reliability data. 57 deployments were identified to August 2020, encompassing a range of manufacturers, locations, device types and foundation systems.**

Each deployment was classified by device type, rated power, number of devices, grid connection, foundation type and location, then identified as either successful, underperforming, curtailed or failed based on defined targets or availability. We found that 18% of deployments failed, 10% were withdrawn from service earlier than intended, and 10% generated less power than was planned. The most common cause of failure was blade failure, followed by generator and monitoring failures.

After initial successful prototypes, failure rate increased between 2006 and 2011, possibly due to increased deployments at high flow rate sites. Subsequent deployments at lower flow rate sites led to a reduction in failure rate to 2018, and current failure rates remain relatively low in spite of a return to higher flow rate sites, suggesting that the sector is now benefiting from lessons learned in pervious failures.

Index Terms—**Failure rate, Learning, Reliability**

I. Introduction

In recent years, technical developments in tidal stream energy have allowed demonstration and pre-commercial deployments to take place. However, some of these deployments have suffered from reliability issues resulting in failures, curtailed deployments, and energy generation below target levels. One reason for the apparently slow development of the tidal stream energy sector is the challenge of operation and maintenance (O&M), which has led to a challenging investment landscape, with investor risk percieved as high due to the cost of operation and maintenance. Consequently, some planned deployments have been halted, and growth in the sector has been slower than forecast. High O&M costs are related to the challenging tidal environment, but are exacerbated by low device reliability. Recent work [1] published by the UK government estimates that O&M represents 17% of the total cost of electricity generation for floating tidal energy devices, and 43% of the total cost for seabed-fixed devices (due to the greater access challenges in the fixed case). 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 current LCOE of tidal stream energy is estimated at £300/MWh [1] with suggested potential 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.

In this article we aim 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 deployment date, location, device type or design, or other project features. Data is presented in anonymised format with the aim of benefiting the sector as a whole.

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A. Reliability

Qualitatively, reliability defines 'the ability of an item to perform a required function under stated conditions for a stated period of time' [2]. Quantitatively, reliability defines the probability that the required function is performed for a set of specified operational and environmental conditions, and a specified period of time. Operating conditions include type and level of stress, use rate, operating profile and environmental conditions. In the case of a tidal stream energy deployment, operating conditions are likely to be strongly linked to reliability, and should therefore be included in any performance statement. Although previous studies [3] [4] [5] have considered the reliability of tidal stream energy, these studies unfortunately rarely report operating and environmental conditions. In this work we made a concerted effort to collect and deduce as many operating variables as possible for each deployment.

B. Learning rates

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 [6] to be around 10% for tidal stream energy.

II. Method

The outline method employed in this paper was to identify all tidal stream energy deployments between 2003 and August 2020, to classify each using the five device characteristics given in Section II-A and the five deployment classifications given in Section II-B, and to determine the outcome of the deployment into one of four categories (Section II-D). By comparing deployment classification to outcome, we then aimed to identify any correlation or relationships between the type of deployment and success or failure.

A. Device Classification

A wide range of devices for the extraction of tidal stream energy exist. 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:

- 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

Three ranges of device rated power were observed in 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 without using categories classified as 'other'.

B. Deployment Classificiation

Each deployment was classified by considering the design of the tidal energy device as described above, and five deployment characteristics:

- Location
- Deployment date
- Duration
- Grid connection (off-grid, small grid (e.g. island), national grid)
- Number of turbines in deployment

C. Data collection method and procedure

In order to review and classify as many deployments as possible, a wide range of data sources were considered, including academic journals, technical reports, articles and press material. There was significant variation in the level of detail available between deployments, but no deployments were excluded due to a lack of information.

D. Deployment Performance

Deployment outcomes were classified into one of four categories: 'failed', 'curtailed', 'underperformed', or 'successful', as given here:

- 'Failed' deployment: A part of the device or connection system under the control of the device developer suffered an unplanned outage, resulting in an aborted operation.
- 'Curtailed' deployment: The intended deployment time was cut short or postponed in order to address a problem likely to lead to a failure, or the same criteria were met due to maintenance or supply chain issues.
- 'Underperformed' deployment: The system did not suffer a failure or curtailment, but did not meet a target for availability, power generation, or operational 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 (see Sections II-D1 and II-D2)
- 'Successful' deployment: Met any specified targets for availability, power generation, or operational time. If no targets were specified, the deployment was deemed successful if there were no reported outages or unplanned breaks in power generation.

1) Availability: Availability 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 [7]: 'full-period' availability (the ratio of hours during a given period when power is generated to the total number of hours in the period) and 'in-limits' availability (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)). We used 'In-limits' availability in this study, since this is the approach adopted by tidal developers who have published data on availability, and allows a comparison between devices independent of cut-in and cut-out speeds. Availability is defined here as A_v and is calculated as given in equation 1:

$$A_v = T_{gen} / T_{in-limits} \tag{1}$$

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. The availability of grid-connected devices may also be impacted by any grid outages or problems, potentially unrelated to the deployment. In the event of such a problem, a device could be recorded as not generating power despite there being no problem with the device or deployment itself. Consequently an off grid device could appear more reliable than an otherwise identical grid connected device. However, no issues of this type were reported in the data discussed here.

We used availability (see Section II-D1) to define whether a deployment was successful or underperforming. The threshold was set separately for each deployment, based on a heirarchy. If a target availability was set by the developer at the deployment outset, this was used (i.e. a deployment which met or exceeded this target was successful, otherwise it was underperforming). If the developer did not define a target availability but defined a target power generation, this and the planned project duration were used to calculate a target availability as described in Section II-D2. If neither target availability or target power generation were defined, we studied descriptions of the planned deployment to ascertain whether the deployment was intended to be a commercial enterprise or whether the target was research and data collection. If the latter was the case, any deployment which met its planned duration without reports of failure was classified as successful. Of the 58 deployments reported, 40 had target availability or power generation. In some research-focussed deployments availability and power generation targets were low, whereas in later stage pre-commercial deployments, target availability values of over 90% were seen. Classification was applied to both ongoing and completed deployments.

2) Site data: Where it was necessary to calculate availability, site data and deployment performance data were used. We recorded the location of each deployment during initial information gathering. A total of 31 seperate deployment sites around the world were identified. Flow velocity values over one spring-neap cycle were collected for each location, regardless of whether deployment availability was published (making this data redundent in some cases, but helping to ensure we avoided any bias in classification). 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, we made an estimate using data from the geographically nearest site for which measured or modelled data was available, with all flow velocity values scaled to the maximum spring tide velocity on the site. Measured data was available in 21 cases (5 sites), modelled data was available in 16 cases (8 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 Fig. 1. This comparison is to illustrate the potential variation between the three sources of data, so all three types are shown. In reality, values were not estimated if modelled data was available, and modelled data was only used if measured data was not available.

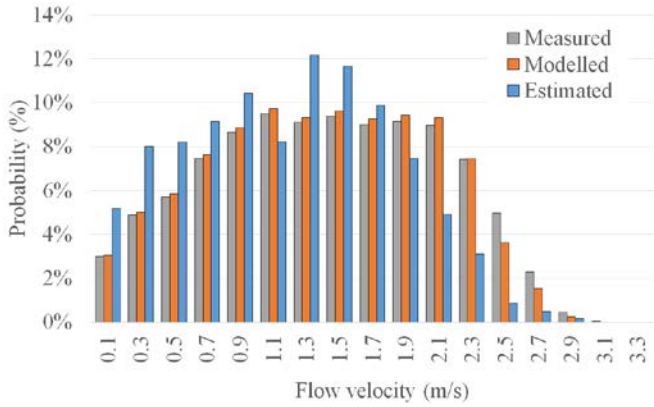

Fig. 1. Statistical distribution of velocity over one spring-neap cycle for an example site: Measured, modelled and estimated as described in Section II-D2.

Fig. 1 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 +/- 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.

III. Results

We identified a total of 57 deployments (as of August 2020). The first deployment was in 2003, after which the mean number of deployments per year was 3.2, with a peak of nine in 2018. We did not identify any deployments in 2004 or 2005, and the minimum excluding these years was one deployment in 2003, 2007 and 2012. Geographically, Scotland had the most deployments (20), followed by France (10) and Canada (7). Deployments were identified in 13 countries overall. We do not feel that deployment location is a key measure, rather a proxy for flow rate, so although location was recorded, results were considered in terms of site conditions during subsequent analysis.

A. Descriptive statistics

Descriptive statistics are presented in Fig. 2. Of the 57 deployments identified, the majority (45, 79%) were of single devices. There were six deployments of two devices (11%) and six deployments of three or more devices (11%). 49 deployments were of horizontal axis turbines (86%), 3 were of vertical axis turbines (9%), and the remaining 5 were of oscillators (9%). The majority of devices (45 deployments, 79%) were not ducted. 10 deployments were of sub-100kW rated power devices (18%), 25 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 34 (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, 13 deployments (33%) 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).

B. Deployment outcomes

Outcomes of the 57 deployments identified are shown in Fig. 3. We found that over half (31 deployments, 54%) were successful, ten (18%) were classed as having failed, eight (14%) as curtailed, and eight (14%) as underperforming. 19 deployments 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 occured during or soon after installation, and was subsequently repaired.

1) Failures: The specific causes of the ten deployments classified as failed fall into four categories, as described below. Two failures fell into multiple categories, so are counted more than once.

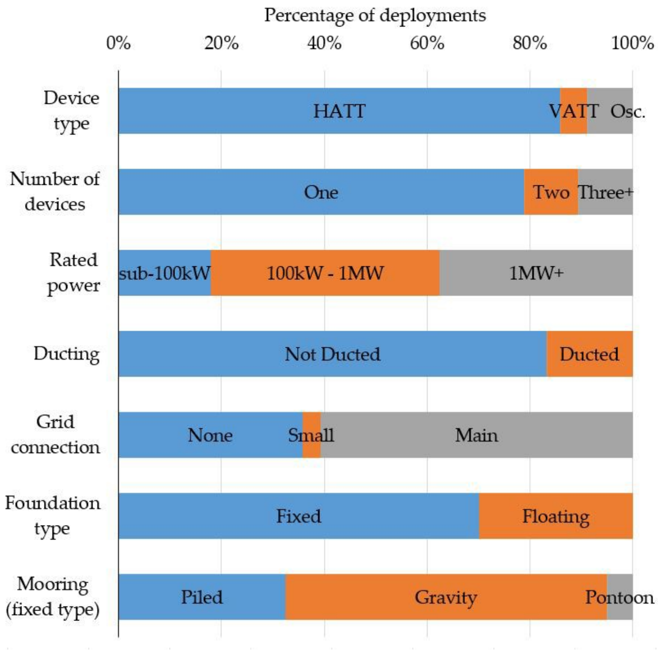

Fig. 2. Descriptive statistics.

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

By blade failure we mean damage to a blade rendering it inoperable, such as by impact (for example being hit by an object during operation), as a result of gradual degredation (for example cavitation), or as a result of design or material errors (for example failure resulting from fatigue).

2) Curtailments: The eight deployments classified as curtailed fell into two categories:

- Underperformance: Five cases.
  Five deployments were withdawn 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.

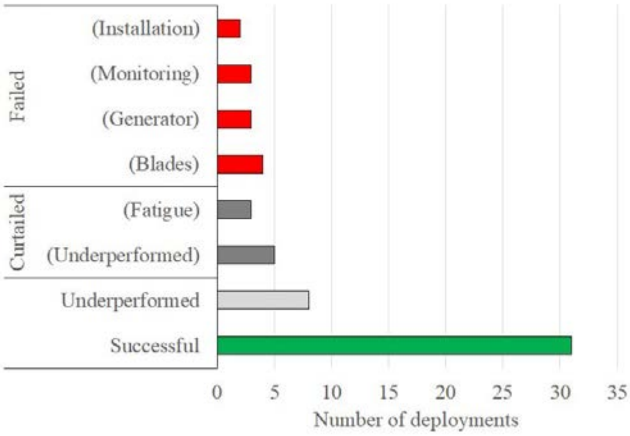

Fig. 3. Deployment outcome results vs category and subcategory.

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.

IV. Discussion

A. Temporal trends

Between 2003 and 2020 we found, in general, an increasing trend in the number of deployment installations per year (see Fig. 5). Although the variation in the number of deployments per year introduces some ambiguity in the interpretation of trends, we also generally found an increasing trend in device rated power over time, with a generally increasing proportion of devices in the 100kW-1MW and 1MW+ ranges being installed each year. Whilst single device deployments remained the most common, deployments of 2 or more devices became more common. The division of grid connection and foundation types showed little variation with time, and whilst horizontal axis devices remained dominant there was little change in the division of device types per year. We found a more complex relationship between time and deployment outcomes over the 2003 to 2020 time period. Using a simplified description of successful and unsuccessful deployments (any deployment classed as underperforming, curtailed or failed was defined unsuccessful, and only a fully successful deployment was classed as successful), Fig. 4 illustrates the success rate of deployments by the year of deployment. This data shows that success rates in the early stage of the industry were high, with a reduction in success rate between 2006 and 2010, followed by an increase between 2010 and 2018, and a period of stability until the end of data capture in August 2020. Of the deployment characteristics described in Section II-A and Section II-B, this trend appears to correlate with maximum flow rate, which was captured with location data. This data is illustrated in Fig. 5.

The reduction in success rate seen between 2006 and 2011 in Fig. 4 appears to be mirrored in the increase in site flow rates illustrated in Fig. 5. We suggest that the greater challenges posed by higher flow rate sites,

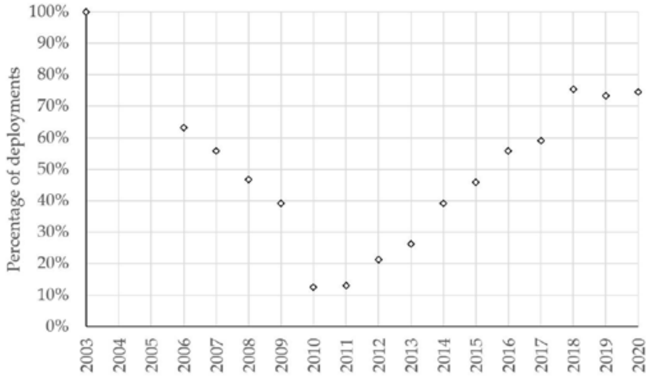

Fig. 4. Deployment success rate vs year of deployment.

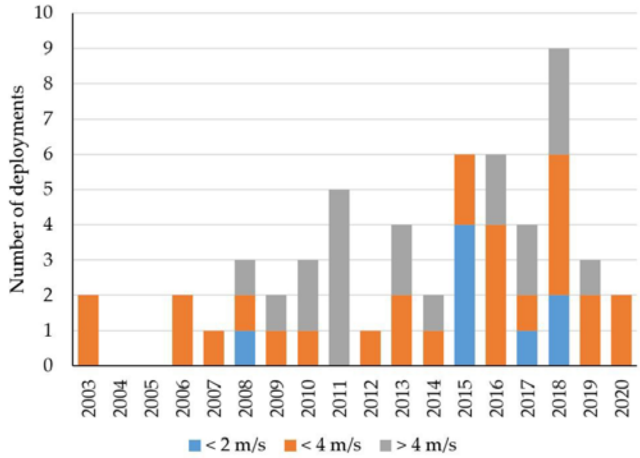

Fig. 5. Deployment site peak flow rate vs year of deployment.

as well as more demanding performance targets set by developers, may have led to the reduction in success rate between 2006 and 2010. Of course these failures are not without value, and unsuccessful deployments provide opportunities for learning from the challenges experienced at these high flow rate sites. During the period between 2011 and 2016, the proportion of high flow rate sites decreased in comparison to the 2006 to 2011 period, which again appears to be mirrored by an increase in success rate with time. It is perhaps possible that the learning gained at high flow rate sites helped achieve this. Since 2016 the proportion of deployments at high peak flow rate sites has increased somewhat (though not to the level seen in 2010 or 2011), but success rate has remained relatively constant. This may be influenced by other factors, but we suggest that the success rate illustrated in Fig. 4 shows four phases:

- 2003 to 2006: With only two devices installed, considerable effort was directed to monitoring and ensuring the success of these early deployments. These research and development deployments were experimental and did not have energy cost targets, meaning maintenance and monitoring were not cost limited.
- 2006 to 2011: After the success of early deployments, devices were installed in more energetic sites. These deployments were often unsuccessful in performance terms but significant learning was

achieved.

- 2011 to 2018: Applying the learning from unsuccessful deployments in highly energetic sites, devices were installed at slightly less energetic locations. By applying learning gained in the previous phase, many of these deployments were successful.
- 2018 to 2020: With learning from the 2006-2011 and 2011-2018 phases, deployments returned to more higher energy sites and many of these appear to be successful.

B. Comparison with wind energy

Though there are significant differences between the tidal and wind energy sectors, they share enough commonalities for a comparison of failure and learning rates to be potentially useful. The wind energy sector reached 1.5 million operating hours (the approximate level reached in the tidal sector as of August 2020) in 1996. A direct comparison between the two sectors in terms of the data presented in Fig.4 has not been possible due to a lack of data on the very early stage wind turbine sector. However, a general comparison is possible. As in the current tidal energy industry, the early wind energy industry experienced a high proportion of blade-related failures [8] [9] (around 20% of failures were blade-related). This data also suggests a failure rate of between 0.025 and 0.09 major failures per wind turbine during 1996, which appears similar to the cumulative tidal sector figure of around 0.065 failures per turbine per year. This gives a baseline for future comparison, and perhaps suggests that the tidal energy sector is following similar trends in learning and reliability improvement to the wind energy sector.

V. Conclusion

We found that over half of all tidal stream energy deployments to date have been successful. Deployments have been undertaken across the world, at a range of scales and with a range of device types. In deployments that failed, blade failures were the most common source of failure.

The available data, though limited, suggests that there may be a correlation between deployment site flow rate and the ultimate outcome of a tidal stream device deployment, particularly during the growth of the tidal stream energy industry (between 2006 and 2011) following early prototype successes. Available data also suggests that in recent years this correlation has weakened, suggesting that lessons learned from earlier deployments may now be permitting successful deployments at high flow rate sites.

Available data appears to demonstrate the impact of learning from earlier deployments in the greater proportion of successful deployments in later years. By sharing lessons learned, the sector can ensure that this learning reduces the likelihood of failure in future deployments, which will drive a reduction in cost of energy and accelerate the ability of tidal stream energy to compete with other renewable energy technologies.

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