BMT Cordah

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Foundations and Moorings for Tidal Stream Systems

Client: The Carbon Trust
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Confidential

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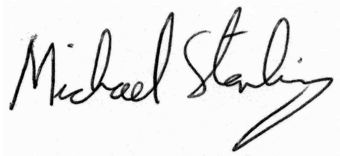
Authors	Michael Starling Alex Scott		21st September 2009
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1 INTRODUCTION

1.1 About the Report

The tidal stream energy system developers share a common challenge. Each device needs to be held on station in a tidal flow in a practical and cost-effective way. The foundations or mooring systems required can form a significant part of the life-cycle cost of the system since they contribute to the capital cost and the ease of installation and maintenance of the device. There are many methods of solving this problem ranging from well-established solutions to new and innovative solutions.

This report is a review of the state of the art in foundation and mooring systems and their applicability to tidal stream systems".

It has been produced by BMT Fleet Technology, BMT Cordah and Mojo Maritime and much of the information derives from the knowledge of BMT and Mojo Maritime.

It was produced by the following team.

- Michael Starling, of BMT Fleet Technology, for his expertise in renewable energy.
- Alex Scott, of Mojo Maritime Ltd, for his expertise in sub sea construction and installation, foundations and moorings;
- Richard Parkinson, of Mojo Maritime Ltd, for his expertise in offshore construction, moorings and installation of tidal and wave energy devices;
- Paul Bowerman, of BMT Cordah, for his expertise on marine mapping and wave and tidal conditions.

The project was managed by Michael Starling and was supervised, on behalf of the Carbon Trust, by Richard Boud.

1.2 Overview of the Report

The report is made up of the following sections.

- an overview of typical tidal stream devices;
- an overview of typical device locations;
- an overview of a foundations and mooring requirement specification;

- a review of foundation and mooring methods;
- a summary of the indicative installation costs;
- a summary of the resulting costs based on the Carbon Trust cost model;
- a summary of the Conclusions;
- suggestions for a directed research programme;
- an overview of the obstacles on the route to market.

The report is supported by the following annexes.

- scope and purpose of a requirement specification;
- example of environmental conditions at a tidal site;
- additional information on cost modelling of foundation and moorings

2 OVERVIEW OF TIDAL STREAM DEVICES

2.1 Sources of Information

The devices listed below have been taken from:

- the list of devices in the BWEA website;
- the list of devices on the EMEC website.

2.2 Characteristics that affect the Foundations and Moorings

The main characteristics of the devices that affect the foundations and moorings are:

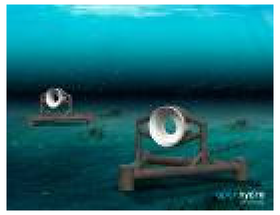
- the type;
  - i.e. if it is rigidly mounted in the tidal stream or is moored in the tidal stream;
  - i.e. is it is fixed to the seabed or floats at the surface or below the surface.
- where in the water column it extracts the energy;
  - i.e. if the energy is extracted from the lower, mid, top level (or throughout) the water column.
- the water depth.

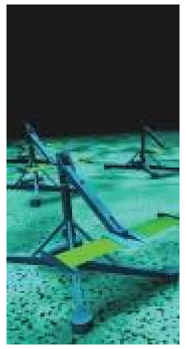
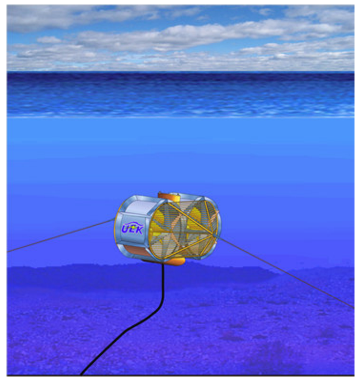
2.3 Tidal Stream Devices

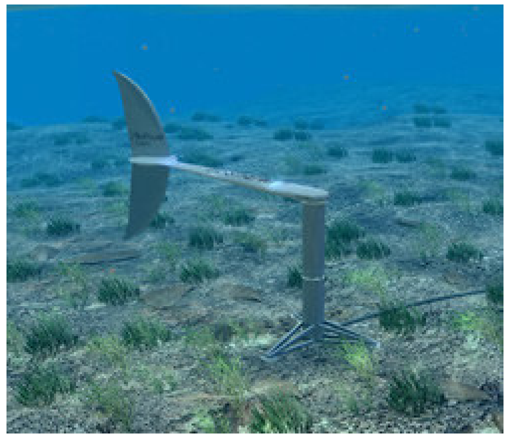
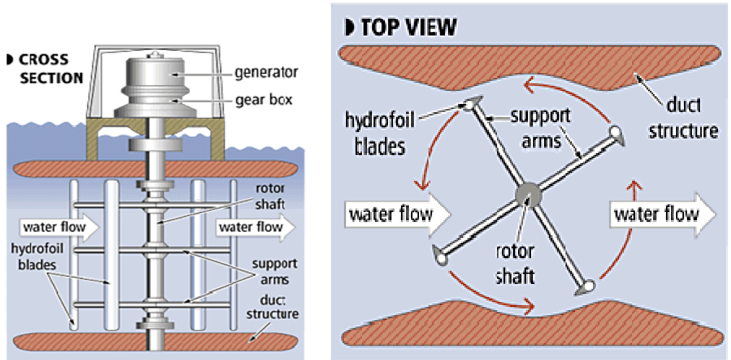
A review was made of the identified tidal devices against the main characteristics of the foundations and moorings. This is shown in Table 1 below. The list is not exhaustive but represents a cross section of current devices that span a broad spectrum of foundation and mooring options. As many devices are still under development inclusion in the list does not imply that the devices are viable, but rather that they represent a challenge in the way in which they are positioned in the tidal stream.

Table Key

✓	Suitable	**O**	Possible depending on severity	**X**	unsuitable

Device	Company	Type	Picture	Type		Energy Extraction				Water Depth	
				Rigid	Moored	Through water column	Sea surface	Lower level	Mid water	Shallow Water <25m	Deep Water <25m
SeaGen	Marine Current Turbines	Open Rotor	 	✓	X	X	X	O	✓	O	O
Rotec Tidal Turbine	Lunar Energy	Ducted Rotor		✓	X	X	X	✓	X	✓	✓
	Tidal Generation Limited	Open Rotor		✓	X	X	X	O	✓	✓	✓
	Open hydro	Ducted rotor		✓	X	X	X	✓	X	X	X
TiDel	SMD Hydrovision	Open rotor		X	✓	✓	X	✓	✓	X	X

Device	Company	Type	Picture	Type		Energy Extraction				Water Depth	
				Rigid	Moored	Through water column	Sea surface	Lower level	Mid water	Shallow Water <25m	Deep Water <25m
Stingray		Oscillating hydrofoil		✓	X	X	X	O	✓	✓	✓
	Hammerfest Strom	Open rotor		✓	X	X	X	✓	O	✓	✓
	Pulse Generation Ltd	Oscillating hydrofoil		✓	X	X	X	✓	✓	✓	✓
Underwater Electric Kite (UEK)	UEK Systems	Ducted		X	✓	X	X	O	✓	✓	✓
Nerus	Atlantis Resources			✓	X		O	O		✓	X

Device	Company	Type	Picture	Type		Energy Extraction				Water Depth	
				Rigid	Moored	Through water column	Sea surface	Lower level	Mid water	Shallow Water <25m	Deep Water <25m
Solon	Atlantis Resources	Ducted								✓	✓
Biostream	Biopower Systems	Vertical Axis Thunniform plane		✓	X	X	X	✓	X	X	X
Davis Hydro Turbine	Blue Energy Tidal Power	Vertical Axis bladed		✓	X	X	✓	X	✓	✓	✓
GCK Technology	GORLOV Helical Turbine	Vertical Axis helical blade		✓	✓	✓	X	✓	✓	✓	✓
Hydrogreen Energy	Hydro kinetic Turbine	Ducted		✓	✓	✓	✓	✓	X	✓	X

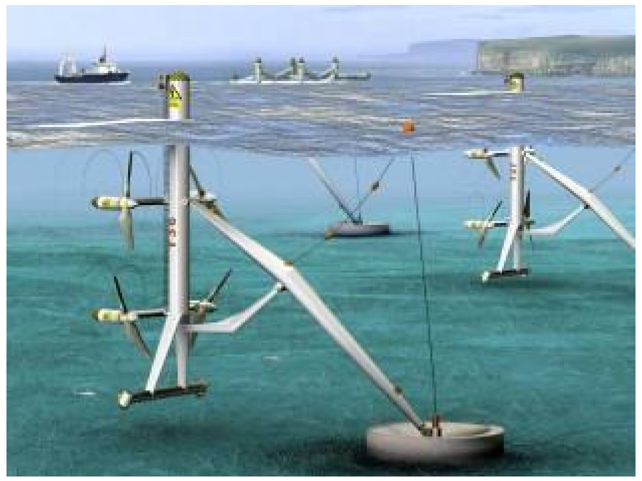
Device	Company	Type	Picture	Type		Energy Extraction				Water Depth	
				Rigid	Moored	Through water column	Sea surface	Lower level	Mid water	Shallow Water <25m	Deep Water <25m
Hydro-Gen	Hydro-Gen	Paddle wheel		X	✓	✓	✓	X	X	✓	X
EVOpod	Oceanflowenergy	Open Turbine		X	✓	✓	✓	X	X	✓	X
	Tidal Stream	Open		✓	✓	X	X	✓	✓	✓	✓

Table 1 Tidal Devices and their Moorings

2.4 Conclusions on Tidal Stream Devices

The technology for tidal stream devices has not yet settled on a design concept in the same way as wind has settled on the design concept of a three bladed, upwind turbine with yaw control. The most advanced developments being tested at sea are only at the pre-production demonstrator and the prototype testing stage.

There are a large number of other devices ranging from those being tested in tanks or at on-shore facilities to design concepts at the initial evaluation stage. Device development is largely dependant on patents of existing designs which may restrict developments. In particular reverse variable pitch, turbine vaning, foundation design, installation methodology or all aspects that have patent controls. However there is little information on how defendable these patents will be.

The result is that there is no generalised requirement for a tidal device foundation.

However, in the opinion of the authors, the most likely design concepts in the short and medium term are likely to be open water devices based on a open or ducted rotor mounted on the sea bed. Foundations and installation methodology is likely to be a key area where devices will vary and developers will try and establish patent protection.

The only exception to this may be shallow water devices based on oscillating hydrofoils. This will become more clear when the results of the prototype Pulse Tidal device installed in the Humber are known.

3 OVERVIEW OF TYPICAL TIDAL STREAM DEVICE LOCATIONS

Tidal stream devices are being designed for a range of locations. The study aims to cover the wide range of potential locations in the UK and around the world for tidal stream devices and produce an indication of the relative difficulty of sites. It excludes locations in rivers but much of the information is relevant to river installations also.

3.1 Relative Difficulty of Locations

The purpose of the overview was to provide a method and some representative data to assess the difficulty of proposed installation sites to the types of sites where tidal devices have been tested.

The proposal to move from pre-production test devices in comparatively sheltered locations to production devices in the full rigours of locations such as the Pentland Firth is a cause of concern. This overview aimed to provide a numerical indication of the relative difficulty of the sites containing the majority of the UK's tidal stream resource.

The methodology used was:

- to select the environmental parameters that most drive the difficulty of a location (Para 3.2);
- to develop a classification system for each environmental parameter to assess the difficulty it gives to the location (Para 3.3). This was done at a workshop on the 4th March 2009;
- to assess the relative importance of the different environmental parameters (Para 3.4);
- to select the favoured locations for assessment (Para 3.5);
- to classify the environmental parameters at the favoured locations (Para 3.6);
- to produce a relative difficulty score for each of the favoured locations (Para 3.7).

3.2 Selection of Environmental Parameters that Drive Difficulty

The study has used the following environmental conditions to classify locations as they are the main drivers of both foundation and mooring installation and also maintenance:

- Tidal Current;
- Water Depths;

- Exposure;
- Bathymetry.

The classification of Tidal Current was based on:

- tidal speed;
- flow conditions (laminar flow vs. eddies and tidal races;
- coastal variation;
- tidal current data uncertainty.

The classification of Water Depths was based on:

- depth at lowest astronomical tide;
- tidal range in relation to depth.

The classification of Weather Exposure was based on:

- survivability extremes;
- co-incident wind and wave windows for installation and maintenance.

The classification of Bathymetry was based on:

- types of seabed;
- proximity to marine hazards.

3.3 Classification System for Environmental Parameters

For each environmental parameter a classification has been defined based on selection form one of five bands, Very Low, Low, Medium, High and Very High, where “Very Low” is the easiest and “Very High” is the most difficult.

Note: The classifications are of how difficult the environmental parameter is for the foundations and moorings and do not take into account the benefit in terms of energy generation from being at that site.

3.3.1 Classification of Tidal Currents

Tidal Speed

Very Low	Low	Medium	High	Very High
<2.5 m/s	2.5 to 3.5 m/s	3.5 to 4.5 m/s	4.5 to 5.5 m/s	>5.5 m/s

Table 2 Tidal Currents - Classification of Tidal Speed

Flow Conditions

Very Low	Low	Medium	High	Very High
Fully Laminar		Mainly laminar except at certain tide conditions		Highly turbulent. Eddies and tidal races

Table 3 Tidal Currents - Classification of Flow Conditions

Variation Across Site

Very Low	Low	Medium	High	Very High
Tide conditions at every device location in the site the same	Two or three tidal conditions within the site	A small number of tidal conditions within the site	An uncertain number of tidal conditions within the site	Tide conditions at every device location in the site very different or very uncertain

Table 4 Tidal Currents - Classification of Variation Across Site

Tidal Current Data Uncertainty

Very Low	Low	Medium	High	Very High
Data from site specific observations	Local area modelling and hindcasts	Area modelling and hindcasts	Low resolution published data	No data available

Table 5 Tidal Currents - Classification of Data Uncertainty

3.3.2 Classification of Water Depths

Depth at Lowest Astronomical Tide

Very Low	Low	Medium	High	Very High
<20	20 m	20 to 40 m	40 m	>40

Table 6 Water Depths - Classification of Depth at Lowest Astronomical Tide

Tidal Range in Relation to Depth

Very Low	Low	Medium	High	Very High
Tidal range has no impact on device (e.g. Deep Water and Low Range)		Tidal range has some impact on device.		Tidal range has a dominant impact on device (e.g. Shallow Water and High Range)

Table 7 Water Depths - Classification of Tidal Range

3.3.3 Classification of Weather Exposure

Survivability Extremes

Very Low	Low	Medium	High	Very High
Protected site. (No wind or wave effect on device)	Semi- Protected site Some protection from the worst of the waves	Open site. (Medium fetch (<100 mile) and fully developed storms)	Very open site. (Long fetch and fully developed storms)	Exposed site. (Long fetch and frequent fully developed storms)

Table 8 Weather Exposure - Classification of Survivability Extremes

Wave and Wind Windows for Installation

Very Low	Low	Medium	High	Very High
Continuous No wind or wave constraint on installation		Constrained Long weather windows Predictable. Useable windows throughout the year		Highly Constrained Short weather windows. Unpredictable. Useable windows only part of the year

Table 9 Weather Exposure - Classification of Wave and Wind Windows for Installation

3.3.4 Classification of Bathymetry

Types of Seabed

Very Low	Low	Medium	High	Very High
Seabed needs no preparation (e.g. Level) Benign geology for mooring or foundation Standard mooring or foundation methods		Seabed Requires Preparation Acceptable geology for mooring or foundations		Uneven seabed (e.g. boulders, large slopes) Challenging geology that constrains mooring and foundation methods Highly specialist methods

Table 10 Bathymetry - Classification of Seabed

Marine Hazards

Very Low	Low	Medium	High	Very High
Open water marine operations		Operations close to shore in a moderately exposed area		Highly constrained marine operations (e.g. proximity to shallow water/land)

Table 11 Bathymetry - Classification of Marine Hazards

3.4 Relative Importance of Environmental Parameters

Some environmental parameters are more important to the difficulty of the site than others. Therefore an assessment has been made of the relative importance of each.

The following definitions have been used to define the relative importance of the environmental parameters.

Low	Low/Medium	Medium	Medium/High	High
1	2	3	4	5

The following values have been given to the relative importance.

Condition	Relative Importance	Value
Tidal Current		
Tidal Speed	Medium	3
Flow Conditions	Medium/High	4
Variation Across Site	Low/Medium	2
Tidal Current Data Uncertainty	Low	1
Water Depths		
Depth at Lowest Astronomical Tide	Low/Medium	2
Tidal Range in Relation to Depth	Medium	3
Weather Exposure		
Survivability Extremes	High	5
Wave and Wind Windows	Medium/High	4
Bathymetry		
Types of Seabed	High	5
Marine Hazards	Medium	3

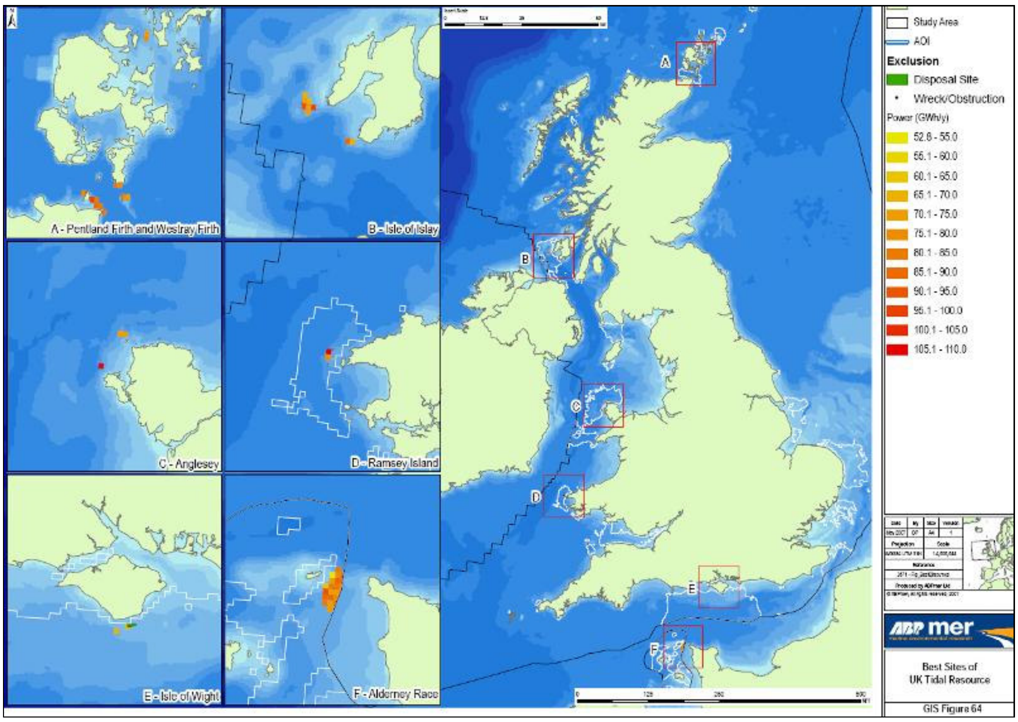
Table 12 Relative Importance of Classifications

3.5 Selection of Favoured Locations

The locations chosen for assessment are those selected in the ABPmer report, quantification of Exploitable Tidal Energy Resources in UK Waters (Map 1). These are:

- Pentland Firth and Westray Firth (A);
- Isle of Islay (B);
- Anglesey (C);
- Ramsey Island (D);
- Isle of Wight (E);
- Alderney Race (F).

Plus the EMEC test site and the Marine Current Turbine site at Strangford Lough.



Map 1 Map of Favoured Locations

Comment [MS1]: The copyright status of this map is unknown

3.6 Classification of the Favoured Locations

The application of the classification system at the favoured locations is shown in Table 13 below.

		Tidal Current				Water Depths		Weather Exposure		Bathymetry	
	Location	Tidal Speed	Flow Conditions	Variation	Data Uncertainty	Depth at Lowest astronomical Tide	Tidal Range in Relation to Depth	Survivability Extremes	Wave and Wind Windows	Types of Seabed	Marine Hazards
A	South Pentland Firth	L Spring rate 2.57m/s	H	H	M	M		VH 12m 50yr sig wave ht	VH	VH	VH
A	North Pentland Firth	M Spring rate 4.63m/s	H	M	M	M		VH 14m 50yr sig wave ht	VH	VH	VH
A	Westray Firth	L 3.6-2.7m/s	L	M	H	M		VH 12m 50yr sig wave ht	VH	VH	VH
A	Pentland Skerries	VH (6m/s) Up to 8m/s	H	M	M	M (average)		VH 14m 50yr sig wave ht	VH	VH	H
B	West Islay	M 4m/s during springs off Orsay	M Eddies at 2,3 & 4 hrs b4 and after HW	L	L	M		VH 14m 50yr sig wave ht	VH	VH	H

		Tidal Current				Water Depths		Weather Exposure		Bathymetry	
	Location	Tidal Speed	Flow Conditions	Variation	Data Uncertainty	Depth at Lowest astronomical Tide	Tidal Range in Relation to Depth	Survivability Extremes	Wave and Wind Windows	Types of Seabed	Marine Hazards
B	South West Islay	VL 2-2.5m/s	M Eddies at 2,3 & 4 hrs b4 and after HW	L	L	M		VH 12m 50yr sig wave ht	VH	VH	H
C	Anglesey	L Max Range = 2.3 to 3.6m/s	M Races over all rocks + shoals. Eddies in locations	VL	L	VH		H 8 m 50yr sig wave ht	M	H	H
D	Ramsay Island	L Max Spring rate =2.57m/s	VH Eddies exist in vicinity of all islets + races between The B & C	VL	H	M		VH 12m 50yr sig wave ht	M	VH	H
E	South Isle of Wight	L Max spring rate = 2.57m/s	L Eddies near land	VL	M	M	average=3 .9m depth = M	H 8m 50yr sig wave ht	M	H	H

		Tidal Current				Water Depths		Weather Exposure		Bathymetry	
	Location	Tidal Speed	Flow Conditions	Variation	Data Uncertainty	Depth at Lowest astronomical Tide	Tidal Range in Relation to Depth	Survivability Extremes	Wave and Wind Windows	Types of Seabed	Marine Hazards
F	Alderney Race	H E side Spring rate = 5m/s	H Eddies of considerable extent	L	H	L		H 8m 50yr sig wave ht	M	H	M
	EMEC	L	L Race off the kirk during SE Gales	L	M	M		VH 12m 50yr sig wave ht	H	H	M
	Strangford Lough	VL	VL	VL	VL	VL		L	L	H	H

Table 13 Classification of Favoured Locations

3.7 Relative Difficulty of Favoured Locations

The resulting relative difficulty of the favoured locations is shown in Table 14 below.

		Tidal Current									Water Depths					Weather Exposure					Bathymetry					Location Score	
	Location	Tidal Speed		Flow Conditions		Variation		Data Uncertainty			Depth at Lowest Astronomical Tide		Tidal Range in Relation to Depth			Survivability Extremes		Wave and Wind Window			Types of Seabed		Marine Hazards				
	Relative Importance	3		4		2		1			2		3			5		4			5		3				
		Class	Score	Class	Score	Class	Score	Class	Score	**Sub Total**	Class	Score	Class	Score	**Sub Total**	Class	Score	Class	Score	**Sub Total**	Class	Score	Class	Score	**Sub Total**	**Total**	**% MCT**
A	South Pentland Firth	2	6	4	16	4	8	3	3	**33**	3	6	3	9	**15**	5	25	5	20	**45**	5	25	5	15	**40**	**133**	**208%**
A	North Pentland Firth	3	9	4	16	3	6	3	3	**34**	3	6	3	9	**15**	5	25	5	20	**45**	5	25	5	15	**40**	**134**	**209%**
A	Westray Firth	2	6	2	8	3	6	2	2	**22**	3	6	3	9	**15**	5	25	5	20	**45**	5	25	5	15	**40**	**122**	**191%**
A	Pentland Skerries	5	15	4	16	3	6	3	3	**40**	3	6	3	9	**15**	5	25	5	20	**45**	5	25	4	12	**37**	**137**	**214%**
B	West Islay	3	9	3	12	2	4	4	4	**29**	3	6	2	6	**12**	5	25	5	20	**45**	5	25	4	12	**37**	**123**	**192%**
B	South West Islay	1	3	3	12	2	4	4	4	**23**	3	6	2	6	**12**	5	25	5	20	**45**	5	25	4	12	**37**	**117**	**183%**
C	Anglesey	2	6	3	12	1	2	4	4	**24**	5	10	3	9	**19**	4	20	3	12	**32**	4	20	4	12	**32**	**107**	**167%**
D	Ramsay Island	2	6	5	20	1	2	2	2	**30**	3	6	5	15	**21**	5	25	3	12	**37**	5	25	4	12	**37**	**125**	**195%**
E	South Isle of Wight	2	6	2	8	1	2	3	3	**19**	3	6	3	9	**15**	4	20	3	12	**32**	4	20	4	12	**32**	**98**	**153%**
F	Alderney Race	4	12	4	16	2	4	2	2	**34**	2	4	5	15	**19**	4	20	3	12	**32**	4	20	3	9	**29**	**114**	**178%**
	EMEC	2	6	2		2	4	3	3	**13**	3	6	3	9	**15**	5	25	4	16	**41**	4	20	3	9	**29**	**98**	**153%**
	Strangford Lough	3	9	1		1	2	1	1	**12**	1	2	3	9	**11**	1	5	1	4	**9**	4	20	4	12	**32**	**64**	**100%**

Table 14 Relative Difficulty of Favoured Locations

Note: %MCT indicates the relative difficulty to the Marine Current Turbine site at Strangford Lough

3.8 Conclusions on Location Difficulty

3.8.1 Method Used

The method used was a subjective one and the individual scores can be subject to challenge based both on the classification given to the environmental parameter and on the relative importance given to it.

In particular, in developing the difficulty scores it soon became clear that the data was not available in sufficient detail on key parameters of the sites for accurate classification. Wide area data on tides, waves, wind and seabed geology are available but not at the specific sites locations. This data has to be obtained by site specific survey and is therefore the commercial property of the site developer.

However the scoring table does give an overall indication of the difficulty of sites in comparison to the Marine Current Turbine site at Strangford Lough and the method did allow the important issues to be raised.

The difficulty scorings are indicative but passed a “sense check” based on practical experience at the workshop comprising BMT, Mojo Maritime and Entec staff.

The scoring system can be modified and/or extended for use at a specific site either on its own or in comparison with other sites. For example when a device developer with experience at one site was assessing the difficulty of another site.

3.8.2 Main Issues

The main issues raised by the location analysis are:

Difficulty

- **Survivability**. Long term survivability, particularly survivability during storms, are a key factor in difficulty. This includes waves, pressure waves and the wave affected zone.

- **Difficulty of Pentland Firth**. That the Pentland Firth sites are significantly more difficult than the MCT site at Strangford Lough. The exposure of the site is a significant factor in this.

Data

- **Need for Site Specific Surveys**. That conditions are so variable within sites that current profiling and seabed geology surveys are required to accurately determine the difficulty of a site.

Weather

- **Weather Impact on Tidal Streams**. That weather has an impact on tidal speeds, peak speed may be significantly higher than highest astronomical predicted tidal speed.

- **Installation and Maintenance Windows**. That periods and timing of slack water (as required for installation and maintenance) vary with the weather and can be difficult to predict.

Seabed

- **Seabed Conditions**. The seabed conditions have a major effect on the design and installation of the device and the mooring of the installation vessels. The geological conditions (obtained by surveys, etc) and geophysical conditions (obtained by samples. coring, etc.) can vary within a site.

- **Cost of Geophysical Surveys**. Geophysical surveys are both expensive and may not yet be practicable in some locations. Therefore foundation designs that rely on data from geophysical surveys may be at a disadvantage.

3.8.3 Risks and Benefits in the Pentland Firth

The only sea area where there is a formal tidal stream energy farm consenting process in place is the Pentland Firth, albeit at an early stage.

In our opinion this is an extremely ambitious location for non-mature technology of the devices, the foundations, the cabling and the support. In particular the developers need to address installation issues at test sites such as EMEC before attempting installation in the Pentland Firth.

If the risks pay off then we will have developed a world class system or range of systems. If they do not pay off then the result could be a loss of confidence and hence investment in tidal stream energy as a whole.

To manage these risks:

- there is clearly a greater need for developers to establish the installation process (or processes) at the concept stage so that the process will develop with the design of the device. This has been lacking in many of the marine renewable devices but will become paramount when moving to more exposed locations so that the installation process can be optimised around shorter weather and tidal windows;

- there is a need to fully understand the survivability extremes at each location.

4 FOUNDATIONS AND MOORING REQUIREMENT SPECIFICATION

The development of a generic foundation type is not possible as there are too many site and device specific variables. However it is possible to generate a generic cardinal point specification that identifisd some of the key requirements.

These relate to:

- Success Criteria;
- Life;
- Loadings;
- Installation;
- Operations and Maintenance.

4.1 Success Criteria

The main success criteria for the foundation mooring should be defined. These are likely to include:

- design;
  - life, survivability and inspection/maintenance intervals.
- Installation.
  - installation time, installation vessels, and installation weather windows.

4.2 Life

A key design parameter is the life of the foundation and/or mooring. Typical leases seem to be for 20 years and therefore, unless it is planned to replace the foundations and moorings, the life should be in excess of 20 years.

4.3 Loadings

The loading on the device, and hence on the foundations or moorings, is critically dependent on:

- the maximum tidal current speed expected at the site;
- the alignment of the current to the device;
- the expected wave loading at the site;
- the turbulence at the site;
- flow induced vibrations;
- impact and snagging.

These loads have to be known and withstood for a variety of fully and partially functioning load cases as well as for a variety of fully and partially completely installed conditions.

4.3.1 Maximum Tidal Current

The maximum tidal current is a combination of the tidal current and any wind or pressure generated variation. This is not known at many of the typical sites.

4.3.2 Alignment

The alignment of the device to the tidal flow may have an effect on the foundation and the moorings. This alignment may:

- vary during the tidal cycle;
- be out of alignment due to alignment errors during installation;
- become out of alignment over time.

4.3.3 Wave Loadings

The wave loadings on the device and its foundations and moorings could be significant, particularly if the device is in either the wave affected zone or the surf zone. Storm loadings on the device structure need to be defined and solutions incorporated at the design stage. It may also be necessary to allow for storm loading conditions for the device during the installation phases in case the foundations cannot be completed within weather windows.

Generally at stormy sites this is not known in enough detail to be able to assess if the device will survive the winter.

4.3.4 Turbulence

The turbulence of the tidal stream will have an effect on the mooring loads and the potential for flow induced vibrations (see below). The level of turbulence at the sites is not known.

4.3.5 Flow Induced Vibrations (Flutter)

The dynamic nature of both the currents, the device and its moorings is likely to lead to situations where there is a risk of flow induced vibrations. This could lead to high frequency and damaging vibrations of a foundation or high amplitude low frequency movements of a moored device.

4.3.6 Impact and Snagging Loads

The tidal flows may have debris flowing in them. It has been reported that a very large purse seine fishing net was swept through the Pentland Firth recently. The need for the foundations and moorings to cope with such impact and snagging loads and its ability to do so is unknown at this stage.

4.3.7 Load Cases

It is also important that the foundations or mooring are capable of withstanding the loadings outside the normal design conditions. These include:

- During Installation;
    - foundations/moorings installed but not completed (e.g. not yet grouted).
- During Operation;
    - normal operation;
    - shutdown.
- With a Failed Device;
    - generator failure;
    - blade failure;
    - control failure.
- Without a Device.
    - device removed for maintenance.

4.4 Installation

The fundamental requirements that have to be specified include:

- Design;
  - The allowable weight of device and foundation.
- Preparation;
  - If the installation site needs any preparation, scour protection, removal of boulders, etc.
- Method Statement;
  - The number of devices to be installed;
  - Will the device and foundation be installed in one operation?
- Location;
  - Depth of water;
  - Location, estuarial, sheltered, exposed;
  - Distance to site from base of operations.
- Planning.
  - The time of year that the installation is to take place;
  - Availability and cost of suitable installation vessels.

4.5 Operations and Maintenance

There are two fundamental areas that need to be specified. These are:

- the effect of operations and maintenance of the device on the foundation/mooring;
- the need for planned, on-condition and corrective maintenance of the foundation/mooring.

4.6 Conclusions on Requirement Specification

In our opinion the specification of the requirements for a foundation or a mooring and the installation process is left too late in the design process.

All device developers should be encouraged to produce concept foundation design or mooring specifications and a concept installation plan at the design concept phase.

These aspects are fundamental to the viability of the development of the device.

5 REVIEW OF FOUNDATION AND MOORING METHODS

5.1 Characteristics that affect the suitability of a Foundation or Mooring

The main characteristics of the seabed that affect the foundations and moorings are:

- seabed geology;
  - i.e. if it is hard or soft;
  - i.e. the depth of any upper soft or softer layer.
- seabed bathymetry;
  - i.e. if it is flat, uneven or sloping and if there are boulders on it;
  - i.e. its stability, particularly if it is mobile of prone to scour;
  - i.e. are the conditions variable through the depth profile.

5.2 Potential Foundations and Moorings

A review was made of the foundation and mooring methods identified against the main characteristics that affect their suitability. This is shown in Table 15 below for foundations and Table 16 below for moorings. The foundations and moorings are looked at in isolation in the tables, however they often share common methods for fixing to the seabed and foundations and moorings may well be used together.

Table Key

✓	Suitable	O	Possible depending on severity	X	unsuitable

Type	Sub-type	Existing Application	SEABED GEOLOGY ← HARD to SOFT →					SEABED BATHYMETRY						
			Granite/ Sandstone	Chalk/ Limestone/ fractured rock	Consolidated sands	Sand/ Gravel	Unconsolidated sands/ Mud	Boulders	Uneven	Sloping	Mobile (e.g. Sand Waves)	Deep Water	Shallow Water	Scour
Gravity Bases														
Gravity Base		Offshore	✓	✓	✓	✓	✓	O	✓	X	O	✓	✓	O
Gravity Base	Caisson	Bridges	✓	✓	✓	✓	✓	O	✓	X	O	✓	✓	O
Monopiles														
Monopile	Driven	Wind farms	X	X	✓	✓	✓	O	O	O	O	X	✓	✓
Monopile	Drilled	Wind Farms	✓	✓	X	X	X	O	O	O	O	O	✓	O
Pin-piled Structures (templates, quadropods, tripods etc)														
Pin pile	Driven	Offshore	X	X	✓	✓	O	O	O	O	O	✓	✓	O
Pin-pile	Drilled	Offshore	✓	✓	X	X	X	O	✓	O	O	X	O	O
Pin-pile	Suction	Offshore	X	X	✓	O	✓	O	✓	O	O	✓	✓	O
Cable Burial														
Rock Cutting		Pipeline and cable burial	✓	✓	X	X	X	O	O	O	X	✓	✓	O
Ploughing		Pipeline & Cable burial	X	X	✓	✓	✓	O	O	O	O	✓	✓	✓
Jetting		Pipeline & Cable burial	X	X	✓	✓	✓	O	O	O	O	✓	✓	✓
Novel Ideas														
Existing Structure	Rig/ Bridge		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Natural Features		Bridge Building	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Type	Sub-type	Existing Application	SEABED GEOLOGY ← HARD to SOFT →					SEABED BATHYMETRY							
			Granite/ Sandstone	Chalk/ Limestone/ fractured rock	Consolidated sands	Sand/ Gravel	Unconsolidated sands/ Mud	Boulders	Uneven	Sloping	Mobile (e.g. Sand Waves)	Deep Water	Shallow Water	Scour
Jack-up	Self Propelled/ Dumb		✓	✓	✓	✓	✓	O	O	O	O	O	✓	✓
Semi-submersible	Self Propelled/ Dumb	Drilling, pipe laying	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tunnel	Cut & Cover	Road Tunnels	O	O	✓	✓	✓	O	O	O	O	O	O	O

Table 15 Potential Foundations for Tidal Stream Devices

Type	Sub-type	Existing Application	USE		SEABED COMPOSITION ← HARD to SOFT →					SEABED BATHYMETRY						
			Device	Installation Vessel	Granite	Chalk/ Limestone	Consolidated sands	Sand/ Gravel	Unconsolidated sands/ Mud	Boulders	Uneven	Sloping	Mobile (e.g. Sand Waves)	Deep Water	Shallow Water	High Scour
Mooring Methods																
Catenary		Installation Vessels	✓	✓	✓	✓	✓	✓	O	✓	✓	✓	✓	✓	✓	✓
Vertical Lift	Tensioned,	Rigs/ SBMs	✓	X	✓	✓	✓	✓	O	✓	✓	✓	✓	✓	✓	O
Anchoring Methods																
Conventional Anchor		Oil & Gas	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	O
Gravity	Clump Weight	Boat Moorings	✓	✓	✓	✓	✓	✓	O	O	O	O	O	✓	✓	O
Gravity	Suction	Offshore Oil/Gas	✓	O	X	X	✓	✓	X	✓	✓	✓	O	✓	✓	X
Pin-pile	Driven	Oil & Gas - Turbines	✓	X	X	X	✓	✓	X	✓	✓	O	O	✓	✓	O
Pin-pile	Drilled	Oil& Gas/ Turbines	✓	X	✓	✓	X	X	X	✓	✓	O	O	✓	✓	O
Pile	Suction	Oil & Gas	✓	X	X	X	✓	✓	✓	✓	✓	O	O	✓	✓	O
Rock Bolts	N/A	Bridge Building	✓	X	✓	✓	X	X	X	✓	✓	✓	X	O	O	O
Shore Anchors	N/A	Cable Pull-ins	✓	✓	✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rock cutting	N/A	Cable Installation	✓	X	✓	✓	X	X	X	O	O	O	O	✓	✓	✓
Jetting	N/A	Cable Installation	✓	X	X	X	✓	✓	✓	O	O	O	O	✓	✓	X

Table 16 Potential Moorings for Tidal Stream Devices

5.3 Further Information on Foundation Types

The table (Table 15 above) shows the most common type of foundations available as well as some unconventional possibilities. It lists the types of foundations available and then categorises where they are likely to be used with respect to seabed conditions. To make the table as comprehensive as possible the geology of the seabed has been used as well as the bathymetric criteria that may impact on foundation suitability.

Seabed Geology

The geology has been graded from hard to soft with typical seabed conditions listed; these classifications are not intended to be exhaustive but indicative of the type of conditions that may be present.

Seabed Bathymetry

The bathymetric data indicates whether the seabed is sloping, uneven or strewn with boulders and also gives and indication of the sea bed stability with respect to sediment transport, the formation of sand waves and scour; water depth has also been included.

Note: Not all of these factors can be represented by a simple Yes or No as to their suitability, as varying degrees of these conditions may or may not allow a foundation system to be used.

Typical Site Conditions

There are two main proposed locations for tidal stream devices, estuarial and open water. The open water sites tend to be categorised by hard seabed conditions with little or no sediment cover as the high current speeds tend to prevent and sediment from settling.

In estuarial sites although sediment may be thin at the highest current speeds; at the edges of the high current areas more sediment may be present and within the scope of mooring positions and possibly foundation sites.

5.3.1 Gravity Base

Gravity bases can be utilised in various forms and may or may not need to be fixed to the seabed. In its simplest form a gravity base anchor or foundation will be lowered to the seabed and its weight will be sufficient to hold the structure in place. In other instances the base may need to be fixed to the sea bed by the use of piles, grouting or the use of suction techniques.

5.3.2 Monopile

Monopiles are one of the most common current methods of foundation for wind farms and are predominately used in sediments such as consolidated sands into which they are piled, although they can be drilled into harder rocks. They offer a firm foundation to structures that consist of a mono tower. The drawback of such a method is that they are expensive to install particularly if drilled and to be economic need to be installed in numbers.

5.3.3 Pin pile

Pin piles are used extensively in the offshore environment and can be driven, drilled or sucked into position depending on the ground conditions. How the piles are used depends on their configuration but typically high strength grout will be used to keep the structure in place or fittings like ball and roller inserts can be used, particularly in mooring applications. Increased holding power in sands can be gained by the use of ‘bell footing’ where the bottom of the drilled hole is expanded out and filled with cement. In softer sands an epoxy can be used to stabilise the sands around the hole.

For tidal applications it is more likely that pin-piles will be drilled due to the nature of the seabed. Drilling of the sockets can be conducted from the surface through a conductor or using subsea drilling rigs. Technology from deepwater oilfield developments is enhancing the ability to develop installation methods for drilling and securing pin piles using subsea drilling rigs operated automatically from the surface.

The performance of these sub-sea drill has yet to be tried in tidal races but is likely to be a key area of development and research.

5.3.4 Existing Structure(s)

It may be possible to attach current turbines to existing structures such as bridges, oil platforms, or even combined with other renewable system such as wind turbines.

5.3.5 Rock Cutting

Rock cutting is a common technique used for the burial of cables and pipelines both onshore and offshore in hard ground conditions. The rock cutting machine will cut a trench to about 2m depth and about 200-300mm wide, for cables, but this could be modified for other applications. Once a trench has been cut, anchoring devices could be inserted in the trench. This would only be suitable for multiple devices as the deployment of rock cutting machinery is expensive, but once deployed can be quick to cut the trenches. This would require more research into the types of anchoring devices that could be used.

5.3.6 Ploughing

Ploughing produces the same profile as rock cutting but is used in softer sea bed conditions.

5.3.7 Jetting

Jetting can be used in consolidated sediments or lighter soils. Jetting is commonly used in post lay cable and pipeline burial and is used to undermine whatever is buried by fluidisation of the sediment so that the item sinks once the jetting ceases the sediment then tends to reconsolidate; could be utilised in increasing the burial depth of anchors to increase holding power.

Air-lifting is a type of jetting using compressed air through a pipe lowered to the seabed. The expansion of the air-bubbles as they rise creates a strong suction which will remove any loose material. This can be used for jetting foundations to the bed rock and the same connections can then be used for grouting thereby ensuring the foundation is grouted to the bed-rock.

5.3.8 Natural Features

Natural features such as rock faces may be used in estuarial sites provided they do not interfere with navigation and other marine activities. There is also the possibility of anchors being located on or above the shoreline, which would reduce installation and maintenance costs.

5.3.9 Jack-up

Jack-up rigs are commonly used for the installation of wind turbines; a simplified purpose built structure could be used as a platform on which to mount current turbines. This means that rather than being a method of installation the Jack-up it self becomes the foundation for the turbines. Issues such as vortex induced vibration, survival air gaps and the leg footings would need to be addressed.

5.3.10 Semi submersible- SWATH (Small Waterplane Area Twin Hull)

Semi submersible / SWATH technology could be used as a platform to deploy current turbines. The vessel would need to be simplified, but it would only make sense if other systems were impractical or more expensive due to site conditions. The semi- submersible would be permanently moored and would then become the platform from which the turbines were deployed. This application is commonly used for drilling platforms and accommodation rigs in deeper waters such as the North Sea. Swath technology is increasingly used in smaller high speed ferries, pilot vessels and is being considered for wind farm support vessels.

5.3.11 Tunnel

An increasingly common method of tunnelling under rivers is to excavate a trench and then sink pre-cast concrete sections into place. This technique could be modified to install concrete bases for turbines although it is unlikely to be economical unless several turbines were to be installed.

5.4 Further Information on Moorings Types

The table (Table 16 above) shows the most common type of moorings available as well as some unconventional possibilities.

The most common application for moorings will be for devices which are designed to be positioned in mid-water column or at the surface; the devices are likely to be positively buoyant using the vertical tension component of the moorings to maintain depth clear of the surface swell and within the optimal tidal stream.

Moorings are characterised by some type of anchor in the seabed with a wire, chain or rope extending from the anchor to the device. The configuration will be either of the Catenary or vertical tension type.

Moorings for Installation Vessels

Even if foundations are used there may be a requirement for the installation vessels to be moored so it is important that both device and installation vessel mooring feasibility are considered at an early stage of the design.

5.4.1 Catenary

Catenary is the most common type of mooring and is most often used with a range of anchor types, depending on the holding ground. The anchor is dropped on the seabed and dragged into place, the anchor embedding as it is dragged, (drag embedment). There is usually a length of chain or wire attached, which acts as a damper by using the weight of the wire to create a catenary, keeping the line of pull at the anchor horizontal which is essential in keeping holding power to a maximum (and preventing uplift at the anchor). The vertical component of the mooring maintains device depth and allows for heave, while the horizontal component reduces the footprint of the device. A chain/wire is then shackled to the wire which goes to the device/ barge. Catenary type mooring systems are also used with piled, suction and gravity anchors.

5.4.2 Vertical Lift

Vertical lift moorings can be embedment anchor type, gravity base, suction or piled type and as the name suggests they resist pull out in the vertical direction. These types of moorings can be installed in almost all types of seabed condition from hard to soft although vertical lift and suction anchors require adequate penetration to fulfil their holding capability and as such cannot be used in areas of shallow bedrock or soft sediments. In the case of shallow bedrock drilled rock sockets would be used in conjunction with suitably designed pin piles and grouting.

Vertical lift moorings can utilise all types of wires and ropes but are mainly used in a mode where for larger forces bundled synthetic fibres (Polyester, Dyneema (Polyethylene Fibre or Nylon) are used. These fibres allow for tensioned moorings such as tension leg platforms and allow varying degrees of stretch to allow load absorption. The moorings are designed to be in permanent tension to avoid shock loads.

Synthetic fibre ropes is a rapidly emerging technology, particularly in the oil and gas sector and in development of wave energy devices, and offers very high strength to weight ratio and very high fatigue resistance and design life. The increased weight to strength ratio allows for reduced footprint in the mooring system, which has an impact on the stability of the device and the power cable connections.

5.4.3 Gravity

Gravity Base Anchors are used for applications requiring vertical lift components. They are used in oil and gas mooring applications particularly in areas of shallow or surface bed rock usually for mooring of support vessels.

They are increasingly used in installing wave energy devices. Gravity base anchors can be installed as a whole or made up of components to reduce lifting requirements. Gravity base anchors are typically reinforced concrete design but may have skirts, spikes or other attachments to increase horizontal friction with the seabed.

5.4.4 Pile

Pin piles are commonly used for more permanent moorings, but they tend to cost more to install. Piles can be either drilled, driven or use suction to be put in place. Drilling is used in the harder bottom conditions, with piling and suction techniques being used in the softer sediments. The advantage of suction techniques over piling is that with piling the life of the pile can be reduced if too much energy is expended in the piling operation. Once a pile has been placed a mooring structure is then inserted and can be cemented in place or ball and roller type fittings can be used.

New techniques of subsea drilling for installing piles are emerging, particularly from the deepwater oil and gas sector. Typically the drill bit and drill string is drilled within the casing and left to form the pile itself. This technology is likely to become significant in the development of offshore moorings for wave and tidal devices in hard seabed conditions.

5.4.5 Rock Bolts

Rock bolts are a land based system with many similarities to piling and not used in the marine environment they tend to be used where the anchoring forces are not high.

5.4.6 Shore Anchors

In some instances the use of anchors on the shore would prove feasible. As an example, at Strangford Lough in N Ireland, the installation vessel anchors were placed very near the shore, in retrospect it would have been possible to place these on the shore by piling, concrete foundation or gravity base. This would have proved cheaper for installation and for the subsequent maintenance and later recovery. The installation of the anchors would also have been quicker, not having to rely on good weather and benign tidal conditions.

Shore anchors been used to moor large redundant oil platforms in sea lochs and fjords in Scotland and Norway and works well in areas such as steep sided fjords or lochs where drag embedment, piling or other moorings would fail. This has been an issue at the EMEC tidal site where steep embankments have created problems for mooring installation vessels using ultra high holding drag embedment anchors.

Consents for shore anchors may be more complicated and may preclude this as an option.

5.4.7 Rock Cutting

Rock cutting is used in cable and pipeline trenching in the marine environment and ashore but no recorded uses of the technique have been found for marine moorings. However it is possible that the system could be modified for producing moorings by providing a key into which an anchoring system could be cemented.

5.4.8 Jetting

Jetting is a technique used commonly in the cable and pipeline industry for post lay burial. It works in medium to soft sediments by liquefying the sediment below the object to be buried reducing its bearing capacity and allowing the object to sink into the sea bed. The sediment returns to its former strength after jetting. This technique could be used in conjunction with other techniques to increase the depth to which some mooring can be installed. Air lifting as previously described could also be used.

5.4.9 Ploughing

Ploughing produces the same profile as a rock cutting machine but in sediments rather than rocks. It is possible that the technique could be used to plough in some type of mooring system; this would require further research to determine the viability of the method and show a benefit in terms of cost, time and effectiveness over other tried and tested methods.

5.5 Maintenance of Foundations and Moorings

In general maintenance requirements vary from basic monitoring for fixed foundations for bottom secured current devices to occasional maintenance for moorings using the tension type configuration and regular maintenance for the catenary type mooring.

Maintenance requirements need to be offset against the installation costs (cost benefit analysis) where the costs for fixed foundations tend to be high, tension type moorings high to moderate, depending on anchor type, and drag embedment relatively cheap.

The maintenance drivers tend to be centred on two main factors:

- do the foundations moorings need to be removed to repair or maintain the device;
- mobility of sediments, scour or mooring lines.

5.5.1 Foundations

Gravity bases and piled foundations and other fixed foundations with the current device attached directly tend to have little or no movement once installed and require minimal maintenance other than monitoring of any long term deterioration with respect to local scour, external impacts, material degradation due to oxidisation or other chemical cause and build up of marine growth. Inspection regimes for these cases could safely be every 2 or 3 years.

With tension type moorings the anchor point may be piled, a gravity base or a special anchor with synthetic fibre bundles attached to the current device, the device will be positively buoyant and will be submerged, the amount of buoyancy determining the vertical component of the tension in the mooring rope. Modern synthetic fibre moorings such as Polyester Speedline has a design life in excess of 20 years as long as the rope is not affected by abrasion or coating damage.

5.5.2 Moorings

Moorings that utilise a catenary pattern will require the most maintenance and require fairly regular replacement of the anchor wires/ fibres/chains. This is caused by what can be severe vibration in he wires caused by vortex shedding acting on the wires. Failure of these lines and attachments is a real possibility.

Failure tends to occur mostly in the thrash zone of the catenary where the catenary meets the seabed. This causes a large reduction in the design life of the mooring. On oilfield moorings for structures such as Single Buoy Moorings or FPSOs design fatigue life of chain moorings can typically be in the region of 2-8 years due to the continual cyclic loads caused by the thrashing of the mooring in the thrash zone.

Wire catenary mooring would wear quicker than chain and as such is not suitable for permanent mooring applications. Due to this, synthetic fibre moorings which are tensioned and do not have a touch down point, are increasingly used and this is very much an emerging technology that will have applications in the marine renewable energy sector.

If this technology is embraced it is feasible to develop mid water tidal turbine devices with a good design fatigue life although installation and O&M may be more difficult. It may be preferable to design the device such that the mooring and flotation elements are fixed and the turbine attached to the flotation section to avoid the necessity for removing the mooring system to carry out repair or maintenance on the device.

5.5.3 Power Cable

Consideration must also be given to the power cable. In fixed foundations this is relatively simple as the cable can be connected to the base and there tends to be no relative movement, complications will only arise if the cable needs to be disturbed during any maintenance or repair of the device. The main issue is scour wear and protection of the cable.

In tethered devices cabling is still reasonably uncomplicated, but again complications will arise if the cable needs to be recovered in the event of maintenance or repair of the device.

In catenary type moorings motion of the system is inherent in the configuration whether devices are at the surface or mid-water, it is inevitable that the cable will also move in relation to the device and the cable configuration will reflect this, in addition the cable will provide additional forces that will affect the moorings. This will bring additional complications if the device has to be recovered for maintenance and repair, and may reduce the life of the cable.

Additionally the nature of the cable suspension in the water column will need to be designed for the bi-directional tidal forces as well as the heave and footprint of the device need to be absorbed. This may use Chinese lantern, lazy S configurations or be tethered to the mooring tendons.

5.6 Conclusions on Foundation and Mooring Methods

5.6.1 Fixed Foundations

In our opinion the most effective method of anchoring a current turbine is to use a fixed foundation, this obviously favours turbines that can be fixed to the seabed. Although some novel methods have been tabled, it is our opinion that the tried and tested methods are the best in the short term.

5.6.2 Mid-water Moored Devices

However, while fixed foundations provide clear advantages several factors may provide openings for development of more novel designs such as mid-water moored devices. It is envisaged that patent restrictions, emerging mooring technology and availability of deep water locations may make moored devices more cost effective.

The emerging development of high technology moorings mid water moored devices may become a more attractive option. The installation costs can be cheaper and simpler and the design fatigue life of modern mooring systems can be in excess of 20 years if well designed. It also allows for optimisation of the height of the device to correspond with the area of strongest flow.

The major obstacle in the design of a mid-water device is the optimisation of the buoyancy of the device to counteract the weight of the turbine and provide adequate vertical component in the mooring line tension. This may restrict the weight and ultimately the output of the device.

Additional advantages may be the speed with which the devices could be deployed as the moorings could be rapidly deployed using suitable anchor handling vessels. While these vessels are expensive, if the installation could be carried out in a short period, this method may become cost effective.

5.6.3 Effect of Patent Protection

Unlike wave energy devices many of the tidal devices use very similar concepts, they are effectively variations on a theme. As a result competition and ultimately patent protection between device developers is common even though there is a desire from all developers for tidal power as a whole to succeed.

The failure of a key device developer is regarded as being detrimental to the confidence in the tidal device development as a whole. However, competition for development is intense and patent protection is likely to be a major issue determining development.

This is in contrast to wave energy developers where the devices have wildly different concepts and there is a generally less competitive environment and ultimately less patent restrictions on design of foundations and moorings.

5.6.4 Early Design of Foundations and Moorings

When considering the design of a device it is essential that the method used to position it within the tidal stream is inherent in the design process. In our opinion too much effort is expended on the device and not enough on its installation and maintenance, which will determine the reliability growth and ultimately the devices feasibility as a commercial generating device. It is the opinion of the authors that the strategy for installation and maintenance should be a key factor in evaluating the feasibility of a device.

6 INDICATIVE INSTALLATION COSTS

The purpose of this section is to assess the installations costs of a foundation or mooting in a structured way in order identify the main influences on the costs.

6.1 General

This section looks at the indicative costs of an installation. The cost of an installation is complex and hinges on many variables; this section has taken the main cost drivers to indicate the scale of the challenge when planning an installation.

Cost of Single Installations

It should be noted that when installing a single device the mobilisation and demobilisation costs of the installation can be higher than the rest of the installation costs combined; therefore the installation of multiple devices brings about real economies with respect to the cost of installation per device.

Cost of Site Investigations

Site investigations are an integral part of pre and post installation work and are very expensive particularly if any coring is required. These costs will increase with the depth below seabed required for analysis i.e. the ultimate depth of the foundations below seabed.

Methods of site investigation to gather seabed hydrographic, geophysical and geotechnical data vary from surface towed and mounted transducers to coring of the seabed.

Typically core drilling is conducted from a jack up vessel but in deeper water locations, leg induced vortexing and operational complexities of operating in the tidal races will affect availability and suitability of vessels for drilling support.

Vibro-coring and Cone Penetration Testing allow for cheaper methods of coring but will be limited on penetration and core recovery meaning that the only effective method may be to undertake drilled boreholes through the harder layers and bedrock to the depth of the foundations. Typically for a drilled/ pin piled location this would be in the region of 5-10m.

Other options for boreholes are drill ships or drilling barges but these are dependant on suitable mooring systems to reduce footprint to an acceptable level. Typically for geotechnical drilling from a floating moored vessel in 20m the footprint required is within 2 metres. This increases with depth.

More expensive options are drilling using Dynamically Positioned Vessels but this is likely to be an extremely expensive option.

Future developments may see the development of seabed mounted subsea geotechnical drills, which may reduce the requirement for specialised vessels. Ultimately the site investigation requirements for foundations, particularly piled/drilled foundations, is likely to be a significant cost driver.

6.2 Cost Bands

In the report all costs are given as cost bands. These bands are defined in Table 17 Installation Cost Bands - Lump Sum Base Costs, Table 18 Installation Cost Bands - Day Rate Base Costs and Table 19 Installation Cost Bands - Cost Adjustment Factors.

Lump Sum Cost Bands					
	A	B	C	D	E
Lump Sum	£2M+	£1M - £2M	£500K - £1M	£100K - £500K	£50K - £100K

Table 17 Installation Cost Bands - Lump Sum Base Costs

Day Rate Base Cost Bands					
	A	B	C	D	E
Day Rate	£50K+	£20K - £50K	£10K - £20K	£5K - £10K	£1k - £5K

Table 18 Installation Cost Bands - Day Rate Base Costs

Cost Adjustment Factors					
	↑↑↑	↑↑	↑	↔	↓
	+ £100,000's	+£10,000's	+ £1,000's	No Effect	Decrease

Table 19 Installation Cost Bands - Cost Adjustment Factors

6.3 Installation Vessel Costs

Installation vessel costs are a major driver of installation costs. These costs take the form of lump sum mobilisation costs and day rate costs. Table 20 below gives an indication of these costs for a range of typical installation vessels.

Vessel Name	Vessel Type	Hull Dimensions LxBxD	Crane Capacity	Moorings Capability	Owner/ operators	Day Rate Cost Band	Capability
Harry McGill	Crane Barge	46x16x2.6m	115t capacity 40m boom	6x 20t winches	Briggs Marine	E	Installation of small moorings, cable work
Molly McGill	Crane Barge	47x11.3x2	115t capacity 40m boom	4x10t winches	Briggs Marine	E	Installation of small moorings, cable work
Dina M	Crane Barge	60x22.4x4	350t		Stemat	D	Installation of Gravity Bases, Construction Support
Svanen	Heavy Lift Vessel	102.75x71.80x6	8700t Gantry	8 point mooring	Ballast Nedam	A	Installation of heavy gravity bases, and piled foundations
Missing Link	Crane Barge	73.9x21.9x5.5	250t@18m	6point mooring system	MCI	C	Installation of moorings and construction support
Atlas	Crane Barge	53.34x20.73x4.25	Crawler crane option	2x 10t triple drum winches	Briggs Marine	D	Installation of moorings and construction support
Microperi	Crane Barge	50.50x21.60x4.25	300t@18m	4x25t mooring system	MCI	C	Construction Support
Anna	Crane Barge	75.95x23.58x5.50	350t@15m	8x17.5t mooring system	MCI	C	Construction Support
Rambiz	Crane Barge	85x44x5.6	max 3300t sheerleg	8 point mooring	Scaldis BV	A	Installation of heavy gravity bases, and piled foundations
Mortlift 1	Crane Barge	43.3x17.6x3.6	68t@ 21.7m	6x10t winches	Humber Workboats	E	Installation of moorings and construction support
Matador	Sheerleg Barge	45.8x20.1x3.6	400t A Sheerleg	6 point mooring	Boon Mees	B	Installation of Gravity Bases, Construction Support
Pontra Maris	Multi Purpose Barge	70x20.4x3	Crawler crane option	6 point mooring	Stemat	C	Cable work, site investigation, Construction Support
Fetsy-L	Multi Purpose Barge	60.4x11.3x2	Crawler crane option	8 point mooring	Stemat	C	Cable work, site investigation
Lisa A	Heavy lift jack up Barge	66x5.46x4	600t@12m	4 point mooring	MCI	B	Heavy lift and piling
Vagant	Heavy lift jack up Barge	43.5x22.5x42			Geosea	C	Construction Support
Excalibur	Heavy lift jack up Barge	60x32x4.24	54m boom		Seacore	C	Heavy Lift, Piling and Site Investigation
Seajack	Heavy lift jack up Barge	61x76x36	1300t@18m	6 point hydraulic driven	A2SEA	B	Heavy lift and piling

Vessel Name	Vessel Type	Hull Dimensions LxBxD	Crane Capacity	Moorings Capability	Owner/ operators	Day Rate Cost Band	Capability
Buzzard	Heavy lift jack up Barge	43x30x4.2		6x1 drum	Geo@sea	C	Heavy lift and piling
Resolution	Heavy lift jack up Barge	130x38x8	300t@25.5		MPI offshore	B	Heavy lift and piling

Table 20 Installation Vessels and their Costs

6.4 Base Case Costs

An estimate has been produced the basic cost parameters for the installation of a single gravity foundation. This is shown in Table 21.

The table is made up of:

- base costs (both lump sum and day rate);
- cost adjustment factors (factors that can both increase and decrease costs).

6.4.1 Assumptions when Developing the Base Case Costs

The following assumptions were made in developing the base cost:

- Design;
  - A gravity base size of 200t.
- Preparation;
  - The seabed is relevantly even with no slopes, large boulders or other obstructions for either the installation vessel or the foundations.
- Location;
  - A suitable base port is within 15 nautical miles of the installation site;
  - Port operations are not constrained by the tides;
  - Small support vessels are available locally;
  - That reasonable shore based support industries are available, cranes, engineering services tool hire etc.;
  - Some local skilled tradesmen are available.
- Planning;
  - A suitable installation vessel is available;
  - Installation takes place in the summer season;

- Weather down time is no more than 4 days per month; (this is quite optimistic considering additional loads on moorings by tides combined with wind loadings, generally operations are affected between 15-20kt wind speeds,. Weather downtime in excess of 50% is more realistic for exposed locations such as the Pentland Firth. Certain activities may be restricted to Neap tides where greater tidal working windows are available).

Basic Costs			Cost Adjustment Factors (Table 19)									
ITEM	Lump Sum (Table 17)	Day rate (Table 18)	Winter Season	Distance to site	No local port	Port Restrictions	Poor industrial infrastructure	Environmental constraints	Tidal Constraints	Sea-bed profile	No of devices	Increased size
Gravity Base	C	-	↔	↔	↑	↑	↑	↔	↔	↑	↓	↑↑
Installation Vessel Mobilisation	B	C	↔	↔	↔	↔	↔	↔	↔	↑	↔	↑↑↑
Installation vessel	B	C	↑	↔	↑	↑	↑↑	↑↑	↑↑	↑↑	↓	↑↑↑
Shore base Rental	E	E	↑	↑	↔	↑	↑	↑	↑	↔	↓	↑↑
Mobilisation of Shore Base	D	-	↔	↔	↔	↔	↔	↔	↔	↔	↑	↑↑
Shore Personnel	-	E	↔	↔	↔	↔	↔	↔	↔	↔	↓	↑
Offshore Personnel	-	D	↑	↑	↑	↔	↔	↑	↑	↑	↓	↑
Transport	-	E	↔	↑	↑	↑	↑	↑	↑	↑	↓	↑
Storage	-	E	↔	↔	↔	↔	↔	↔	↔	↔	↓	↑
Support Vessels	-	D	↑	↑	↑	↑	↑	↑	↑	↑	↓	↑
Cable Installation	-	B	↑	↑	↑	↑	↑	↑	↑	↑	↓	↑

Table 21 Indicative Bases Costs and Cost Adjustment Factors of Installing a Foundation

6.5 Commentary on the Cost Adjustment Factors

The following section identifies the cost adjustment factors that could change (i.e. usually increase) the costs.

6.5.1 Installation During the Winter Season

The time of year that installations are carried out is critical, the accepted season around the UK for minimising disruption due to poor weather is between April and October; poor weather can be defined as sea states of >2m and wind speeds in excess of 12m/s, these represent typical operation parameters for barges and cranes respectively. However, there are advantages to installing in the winter months if the weather window required to carry out the installation is short. It is more likely that suitable installation vessels are available and that the day rate of these vessels will be lower than the summer months. This price advantage has to be offset against the likelihood that the job will take longer.

In the summer months it will be harder to get vessels on short term charter and the daily hire costs may well be punitive.

6.5.2 Distance to Site

The further an installation site is from the base of operations the more problems arise in servicing the requirements of the installation vessel and crew with added costs due to time delays and additional bunker costs. If the installation vessel has to return to base to load installation equipment or current devices, then the distance from the base of operations will play a part in the time required for the installation and hence the cost.

6.5.3 No Local Port

In addition to those drivers mentioned in the previous paragraph having no local base of operations means that the installation vessel needs to be largely self sufficient and that the ability of the vessel to stay on station becomes important. This may mean that a larger and more expensive vessel will be required as well as additional support vessels.

6.5.4 Port Restrictions

The nature of any port may mean that there are restrictions on when vessel can sail, these may be due to the port having lock access, insufficient water at low tides or priority given to other commercial traffic.

6.5.5 Poor Industrial Infrastructure

If there is no local infrastructure with respect to the availability of trade skills, and equipment, these will need to be brought to site and accommodated. This usually means that costs are considerably increased because men and materials have to kept on hire even when not needed to ensure availability.

6.5.6 Environmental Constraints

It is quite common for there to be environmental constraints on a project. These can be restrictions on the time work can be carried out due to migratory birds, marine mammals, breeding seasons etc or if near land, limits on the amount of noise, particularly with piling operations. These can potentially have huge cost impacts, particularly if there is any slippage in a project timescale that then meets these limitations with projects subsequently being delayed to the next season.

6.5.7 Tidal Constraints

It is axiomatic that there will be operational constraints imposed by the tidal conditions at the site, the nature of tidal stream devices requiring high tidal currents. However, there may be additional constraints imposed by local tidal conditions that limit the scope of operations to more narrow working windows. In addition the higher the tidal stream speed and additional factors such as wave interaction will increase the size and strength of foundation required and hence the cost.

6.5.8 Sea-bed Profile

There may be additional factors with the seabed such as steep inclines uneven surfaces, the presence of large boulders that will necessitate the foundation being modified to suite or the seabed being prepared before installations can commence.

6.5.9 Number of Devices

If installing only one device the cost per kWh is likely to be high, however by installing multiple devices, economise of scale will come into play and reduce the cost.

Main cost driver benefits are the spreading of the mobilisation and demobilisation vessel costs, optimisation of the installation program, ability to negotiate better installation vessel rates and secure better availability or possibly even develop purpose built installation capability.

6.6 Conclusions on Installation Costs

Determining the cost of an installation is complicated and entirely dependent on the location of the installation site, which is not controllable by the installer. Looking at the cost drivers given in this section it is obvious that the more devices that are installed the less the cost per unit for installation.

6.6.1 Availability of Vessels

Installation vessels and their availability are another cost factor. The availability of suitable vessels is poor; most construction vessels have been designed for other industries such as offshore oil & gas, port construction, dredging and bridge building. These vessels are designed for industries where the cost of installation is not such a big cost driver and there are no great imperatives to reduce costs.

6.6.2 Future Availability

The future availability of vessels is also subject to changes driven by factors outside the control of the tidal industry. This includes the relocation of vessels NW Europe to regions such as the Caspian and Middle East and the construction of offshore wind farms has removed many suitable vessels on long term lucrative charters. It is likely that the development of offshore wind farms will maintain a high demand for suitable support vessels and that this demand is likely to increase over the next few years with several large Round 2 offshore wind projects and ultimately the development of the Round 3 projects absorbing large fleets of support vessels. Strategic consideration of vessel availability is a key aspect in planning the development of tidal devices, particularly when larger arrays are proposed.

6.6.3 Resulting Installation Methods

The installation methods of these devices are often dependent on what vessels are available rather than what would be most suitable. Vessels often need significant modifications in order to be utilised which drives up the cost of mobilisation and demobilisation. As the number of installations of these devices increases, more pressure will be put on vessel availability, and day rates will increase. The only solution to this is for more suitable vessels to be built; this will not happen commercially unless owners can see a demand of at least 10 years.

6.6.4 Purpose Built Vessels

Some developers are currently looking at the feasibility of procuring purpose built vessels to install their devices. Typically new-build or modified barges with lifting capability are being developed. This is a prudent strategy as the barge can be built or modified to the device installation requirements, notably:

- Improvised mooring arrangements for use in tidal streams;
- Development of installation capability and expertise;
- Improved lifting and handling systems tailored to the device;
- Cable laying and connection capability;
- Operations and maintenance capability.

7 COMPARATIVE COSTS OF FOUNDATION AND MOORINGS INSTALLATION

One of the supplementary questions asked by the Carbon Trust related to the likely installation and maintenance cost of foundation for a seabed mounted device and the moorings for a mid stream moored device.

The reason for the question was that there are many more seabed mounted devices being proposed than mid-stream devices and the Carbon Trust sought information to help decide if it was worth investigating more mid stream devices.

7.1 Basis of the Costing

The basis of the costing was:

- a nominal 1MW device;
- a capacity factor of 40%;
- a life of 20 years;
- a discount rate of 15%.

The cost of the Foundation hardware and the Mooring hardware was excluded as it will be device specific, the cost were for the installation and maintenance only.

7.2 Summary of the Findings

The costing was done using the Carbon Trust Cost Estimation Methodology spreadsheet[1]. The input data spreadsheets have been provided separately but a summary is shown in the figure below.

The methodology calculates energy costs per kWh base on a base case, bounded by an optimistic and a pessimistic assessment. The figure shows a normalised cost of energy for the base case foundation and the base case mooring.

The values have been normalised so the foundation base case with 7 devices installed and a discount rate of 15% equates to 1.

[1] The Cost Estimation Methodology is based on an excel-based cost collation tool produced to accompany the report “Cost estimation methodology: The Marine Energy Challenge approach to estimating the costs of energy produced by marine energy systems” B/15992/C001/069 Version 1.0 commissioned by The Carbon Trust and carried out by Entech UK Ltd in May 2006.

The findings show that there is a significant opportunity for mooring devices to be substantially cheaper than devices on fixed foundations (Figure 1).

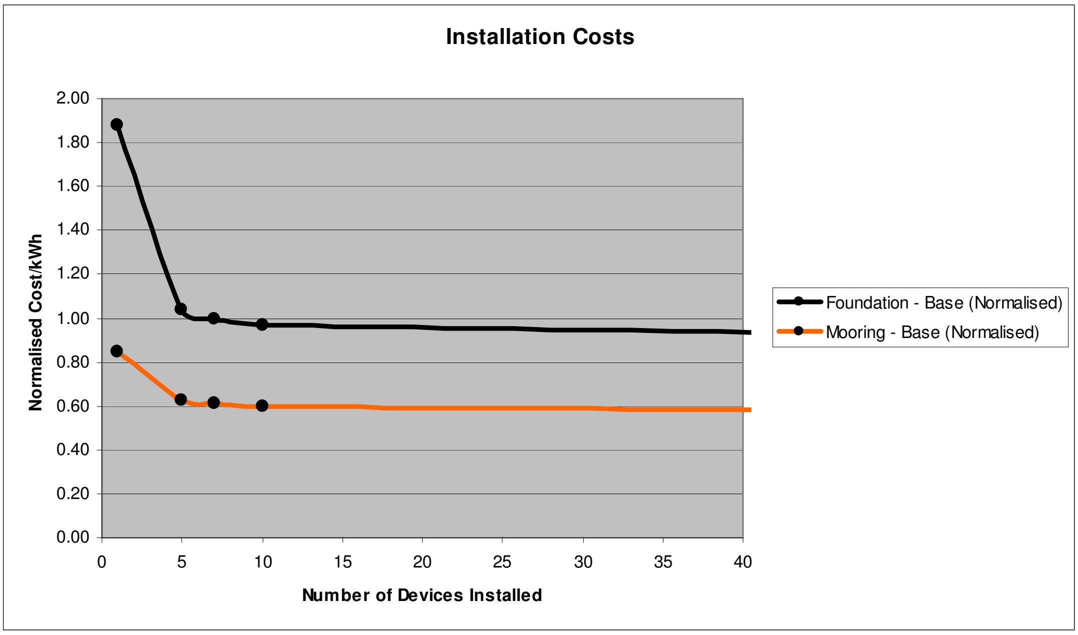


Figure 1 Normalised Installation Costs

Cost Reduction Profile

The cost reduction profile comes from the amortisation of fixed costs (such as mobilisation) over the number if devices installed. It does not include any aspect of cost reduction resulting from technological advances, cost of capital or the economies of scale of larger projects.

Absolute Values

The absolute cost for installation are in the range 10 to 38 pence per kilowatt-hour. These cost should be used with considerable care. The reality is that costs can only be estimated after an installation method statement has been produced and such statements will be device and location specific.

Relative Values

The calculations show that the cost of a mid water mooring compared with a foundation is similar for the optimistic case but foundation devices are significantly more expensive for both the pessimistic and base cases.

The reason for this is that the installation of heavy and large single foundations requires significantly larger vessels and therefore significantly larger expense if the vessels are required for longer.

7.3 Limitations of the Cost Modelling

As mentioned above the installation cost can only really be estimated after device and site specific method statements have been produced.

The cost of inspection and maintenance of a foundation and/or mooring cannot be estimated in isolation from the cost of inspection and maintenance of the device. This is especially the case with a moored device where it may have to be brought in periodically to maintain the device and this action will also maintain the moorings.

8 CONCLUSIONS

8.1 Integration of Foundation Design with Device Design

The foundation design needs to be an integral part of the device design and not an afterthought. To make sure this happens there should be a Foundation Requirement Specification as part of the suite of Device Requirement Specifications.

8.2 Foundation Design - Need to use tried and tested designs

There are a range of foundation options available. In our opinion the tried and tested foundation methods for marine applications are the best option at this stage, this means either monopiles or gravity foundations. However, it is important that new and emerging technologies such as mid water moored devices are not excluded from consideration due to transfer of mooring technology from the oil and gas sector and limitations imposed by patents.

8.3 Mooring Design - Need to demonstrate feasibility

There are considerable uncertainties in the use of mid-water moored devices. The moorings will have to be stable for a long period of time and will have to hold the device steady in reversing tidal flow. In addition, the tidal range will be significant in proportion to the depth and therefore there will be considerable change to the mooring and the cable connection over the tidal cycle. Deep water moored installations, such as Floating Production, Storage and Offloading (FPSO) vessels do this by “S” bends and in the cables supported by mid-water buoys, but there will be insufficient depth to do this with tidal devices. With the emerging technology of tension synthetic moorings, with proven reliability and fatigue, the use of mid water and moored tidal devices becomes more feasible.

If these devices are to progress then the specification and design of the moorings should be looked at very carefully, not least because of the problems with connecting cables.

8.4 Installation of Single Devices and Series Installation

The foundation design and the installation concept have to be capable of both single device installation (to de-risk both the design and the process) and series installation. There are risks that:

- designing the foundation for a single prototype installation may compromise the ability to design for the long term economies of scale;

- designing the foundation for the long term economies of scale may compromise the ability to design for a single installation.

For example if the foundation is designed to take advantage of a specialist vessel then this vessel might not be available for a single installation.

8.5 Installation Vessels - Need to investigate the "ideal" vessels

The lack of availability of suitable installation vessels is driving up costs and building a special-to-type tidal stream device installation vessel may reduce costs. Such a vessel would need to be capable of lifting the types of devices, operating in high tidal currents, holding on station (and this could mean a jack-up, spud legs, dynamic anchoring or dynamically positioned vessels) and have facilities for the associated completion works such as grouting or levelling.

There are a variety of ownership options for such a vessel ranging from pure private sector ownership, through leading developer long term charter (like the Resolution for wind farms), government long term charter (like the emergency response tugs held at strategic points around the coast to help vessels in distress and threatening the coastline) to outright government ownership (like defence support vessels).

8.6 Maintainability - Need to design for ease of maintainability

Maintainability of a foundation or mooring is crucial to its through life costs. For foundations the need to carry out inspections, if required, is a major cost driver. Inspection might require the use of divers (and the devices will be in difficult diving conditions) and the removal of marine growth (which will be time-consuming in an environment where weather windows will be short).

For moorings the relaying of moorings will be major cost driver and design should focus on maintenance without the need to remove moorings.

9 RECOMMENDED ARRAS FOR FURTHER RESEARCH

The following section provides our recommendation for a directed research programme.

9.1 Suggested Research to Reduce Risk

The study identified the following generic risk to tidal device deployment that could be addressed by the directed research programme.

9.1.1 Risk 01 – Survivability: Survivability of foundations in high tide and storm environments.

Much testing has been done on the performance of pre-production tidal devices but there has been less testing of their foundations. As a result there is still considerable uncertainty on the stability of foundations, particularly over the winter storms.

It is suggested that the testing of foundations is decoupled from the testing of devices and representative dummy gravity foundations with an appropriate dummy device, say of 250, 500 and 1,000 tonnes, are placed in the Pentland Firth and surveyed for damage and movement over a period of two years.

The aim of the study would be to gain data on the long term stability of what is expected to be the most common form of foundation, concrete gravity foundations, quicker and at less cost and risk than testing functional devices in the same area.

There is an opportunity to install these in May 2009 using the resources that will be deployed at EMEC to install a test device.

9.1.2 Risk 02 – Cables: Laying, Burying Securing and Connecting Cables in High Tidal Streams.

All devices will require intra-array and export cables. These have to be laid in areas of high tidal flow which are often uneven and rocky and survive for 25 years.

It is suggested that research is undertaken to investigate how cables can be laid, buried, secured and connected in the three main tidal energy areas, the Pentland Firth, the Anglesey Skerries and Alderney.

The aim of the study will be to give all device and project developers detailed information on the design of the cable, the installation method and the securing method and also indicative installation and through life costs.

9.1.3 Risk 03 – High Cost of Installation: Concept Design of a Specialist Vessel.

Current installation concepts are based around the installation of single devices using existing assets. Larger scale deployment would justify the development of specialist vessels as large scale development of offshore wind led to specialist vessels.

It is suggested that a an outline design study (or range of designs) of what such a vessel might look like is produced together with its capital cost and the resulting installation cost. The study could also look at financing, operating and ownership options. The study should include options for an installation vessel, a combined installation and maintenance vessel and a maintenance vessel.

The aim of the study would be to develop design concepts that will reduce the cost of installation for series installation of a large number of devices.

9.2 Suggested Research to Investigate Opportunities

9.2.1 Opportunity 01 – Mid Water Devices: Feasibility of Mooring Systems.

There are a range of mid water devices proposed that use mooring systems connected to seabed mounted anchors. These have the potential for significant cost savings but the feasibility of the mooring system to hold the device in the right position, the alignment over time and the connection of a cable to a moving device and keeping the cable from being damaged is uncertain. In particular the resistance of the system to flow induced vibrations that could result in large movements of the device or vibrations that damage it is uncertain.

It is suggested that a study is undertaken to assess the feasibility of mid water mooring systems. This could be a theoretical study or a study backed up by water tank testing. The study should also consider the likely marine growth on the moorings and its effect in the study.

The aim of the study would be to give all mid-water device developers guidance on technology available for developing moorings for their device and indicative installation and through life costs.

9.2.2 Opportunity 02 – Surface Moored Devices: Possible Design Solutions.

There is considerable available technology for mooring passive structures on the sea surface over long periods of time. FPSOs, SPMs, Drilling and production rigs, Lightships for example.

It is suggested that a study is undertaken to investigate if devices, currently planned for sea bed or mid water installation, could be surface mounted and if so what such a system would look like.

The aim of the study would be to give all device developers information on alternative installation methods and indicative installation and through life costs.

9.3 Research Programme Participants

The tidal energy industry is driven by the perceived value of its Intellectual Property Rights (IPR). At the moment device developers see the foundation or mooring system as part of their developing IPR and will not share information. This means that this type of research would have to be funded by government (or its agents) and done by an organisation that does not have equity stake in a tidal stream device. The results would then be disseminated.

If tidal device developers did not regard the foundations or moorings as IPR then the research options also include:

- funding a device developer to do the work provided they disseminate the results;
- a joint industry project between device developers, possibly seeded with government funding;
- funding an installation contractor to do the research provided they disseminate the results.

10 OBSTACLES ON THE ROUTE TO MARKET

10.1 Routes to Market Template

The following technology and project routes to market templates (Figure 2 & Figure 3) were used to classify the obstacles identified.

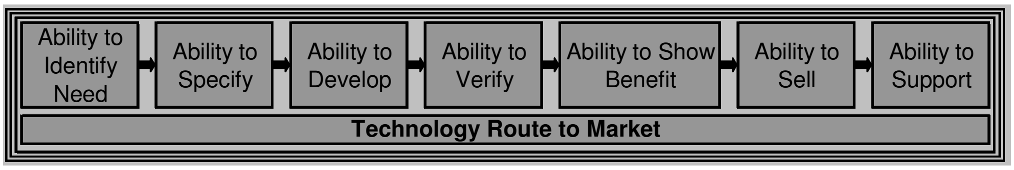


Figure 2 Technology Route to Market

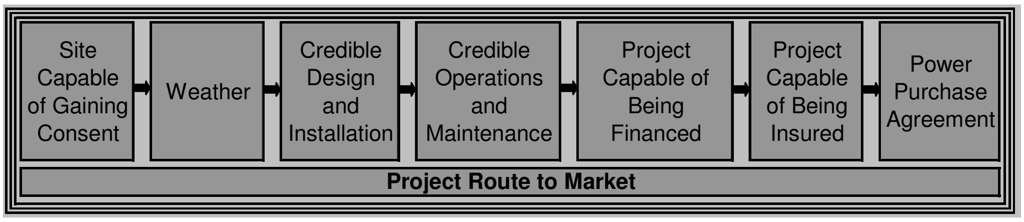


Figure 3 Project Route to Market

10.2 Conclusions and Directed Research

The following tables (Table 22 & Table 23) show how the conclusions and recommendations for directed research fit in both the technology and project routes to market.

Technology Route to Market

Technology	Conclusions	Directed Research
Ability to identify need		
Ability to specify	Integration of Foundation Design with Device Design	
Ability to develop	Foundation Design - Need to use tried and tested designs Mooring Design - Need to demonstrate feasibility	Opportunity 01 – Mid Water Devices: Feasibility of Mooring Systems.
Ability to verify		
Ability to show benefit		Opportunity 02 – Surface Moored Devices: Possible Design Solutions.
Ability to sell		
Ability to support		

Table 22 Technology Route to Market

Project route to Market

Project	Conclusions	Directed Research
Capable of gaining consent		
Weather		Risk 01 – Survivability: Survivability of foundations in high tide and storm environments.
Credible Design and Installation	Installation of Single Devices and Series Installation Installation Vessels - Need to investigate the “ideal” vessels	Risk 02 – Cables: Laying, Burying Securing and Connecting Cables in High Tidal Streams.
Credible Operations and Maintenance	Maintainability - Need to design for ease of maintainability	
Capable of being financed		Risk 03 – High Cost of Installation: Concept Design of a Specialist Vessel.
Capable of being insured		
Power purchase agreement		

Table 23 Project Route to Market

11 ANNEX A - SCOPE AND PURPOSE OF A REQUIREMENT SPECIFICATION

The purpose of a requirement specification is to be the tool that drives a design from the design concept to a design solution that is both technically possible and financially possible.

This is an iterative process and can be considered as a process that circles in on the solution as shown in Figure 4 below.

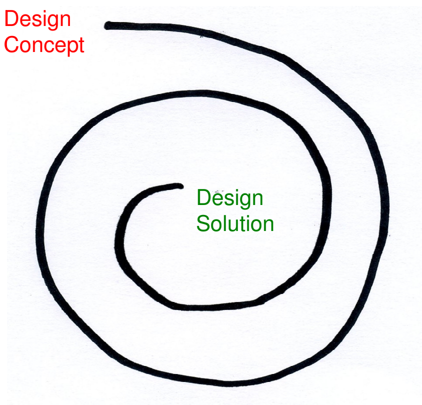


Figure 4 Circling in on a Design Solution

As the process iterates, more and more of the design, installation and operational issues have to be considered and incorporated into the requirement specification and the following gives a generic framework for this.

The requirement specification is a fundamental tool in engineering design and development, yet it is surprising how many designs and developments are attempted without one.

11.1 Phases of Development

The sequence of any marine energy project, oil & gas or renewable energy, can generally be considered to go through the following phases (Figure 5).

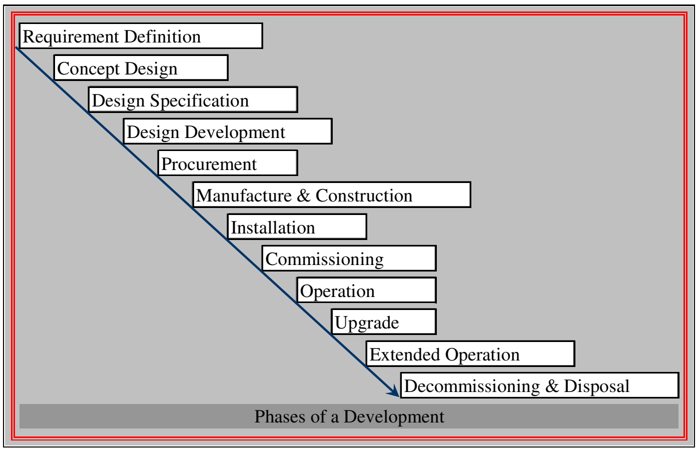


Figure 5 Phases of a Marine Development

11.2 Phases of an Installation

The sequence of a marine installation can generally be considered to go through the following phases (Figure 6).

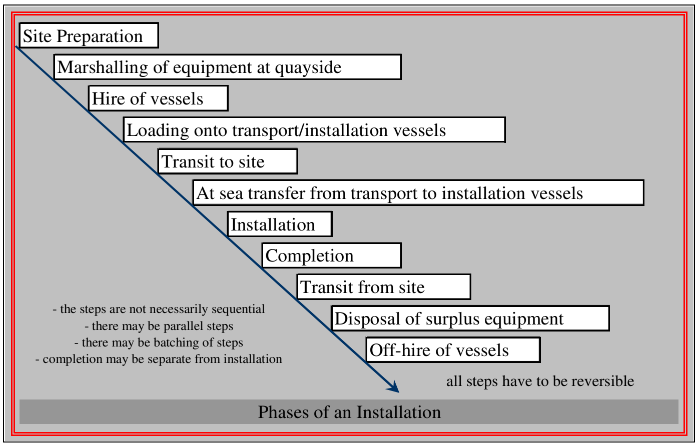


Figure 6 Phases of a Marine Installation

11.3 Installation Cost Drivers

The factors that affect a marine installation, and hence drive the cost, include (Figure 7).

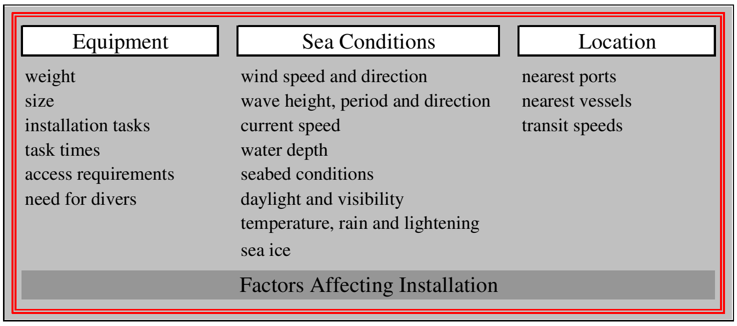


Figure 7 Installation Cost Drivers

11.4 Phases of Operation

The operation of a marine installation can be considered to include the following stages (Figure 8).

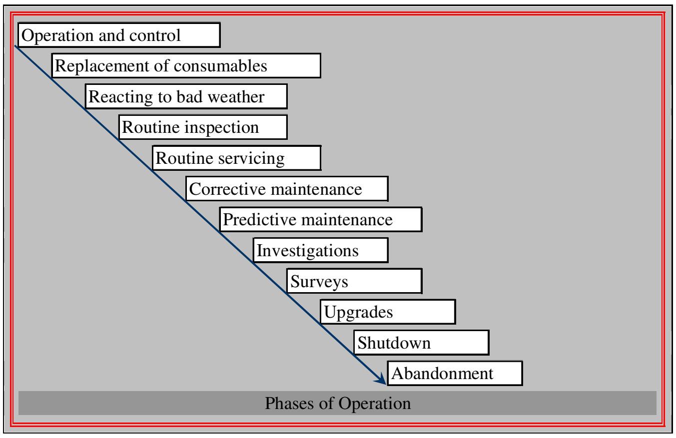


Figure 8 Phases of Marine Operations

11.5 Factors Affecting Operations

The factors affecting marine operations, and hence drive the cost, include (Figure 9).

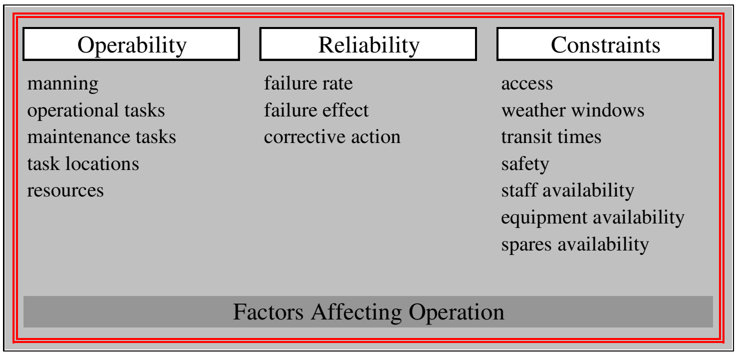


Figure 9 Operations Cost Drivers

12 ANNEX B - EXAMPLE ENVIRONMENT IN THE PENTLAND FIRTH

This annex gives some supplementary information on the environment in the Pentland Firth as an example of one of the harshest environments for tidal energy devices. The environment has been described in terms of:

- the difficulty of the location;
- the geology;
- the ecology and marine life;
- the propensity for marine growth;
- possible marine growth solutions.

12.1 Difficulty of the Location

The typical sites in the Pentland Firth are in high to very high tidal current, medium to deep water depth and are exposed. i.e. they are in a very difficult location.

12.1.1 Tidal Currents in the Pentland Firth

There are both strong tidal currents and large spring/neap variations in the Pentland Firth. Figure 10, Figure 11 and Figure 12 below show the variation in tidal current magnitude over a spring/neap cycle for a location in the Outer Firth between Stroma and Muckle Skerry. This data has been derived from the 1km Orkney model developed by POL.

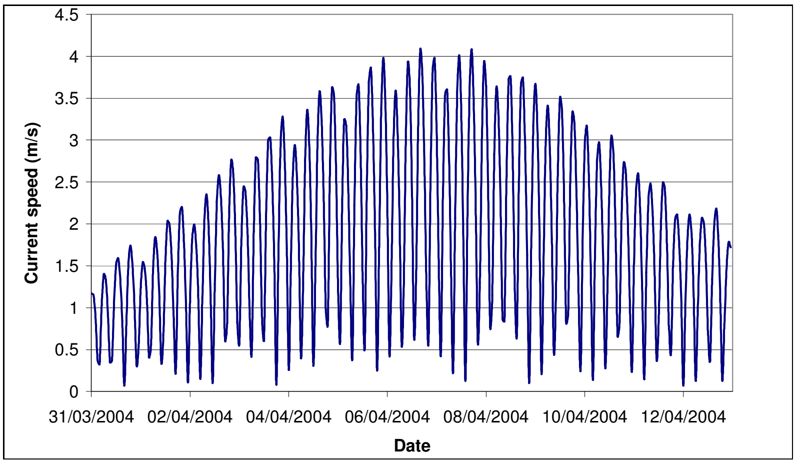


Figure 10 Tidal Currents Cycles in the Pentland Firth

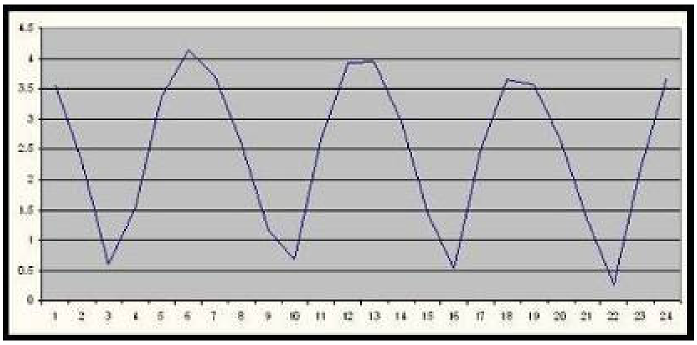


Figure 11 Tidal Currents Cycles in the Pentland Firth - Spring Tide

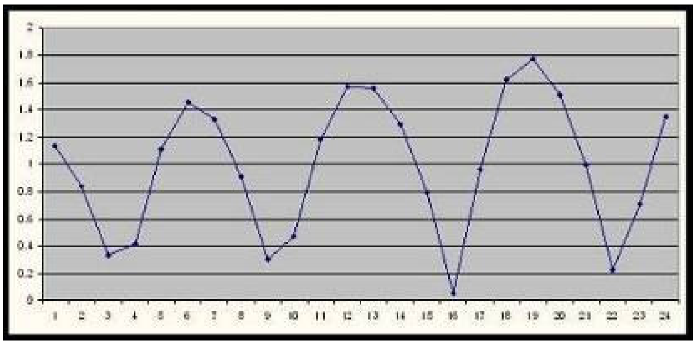


Figure 12 Tidal Currents Cycles in the Pentland Firth - Neap Tide

Local Conditions

High tidal flow sea areas are likely to have local conditions. The strong tidal currents in the Pentland Firth give rise to eddies, overfalls and tidal races in a number of locations. These are areas of turbulence, where current speeds and directions may be highly variable and consequently may have be avoided as sites for tidal energy devices.

Eddies

Eddies occur in the lee of Swona, Stroma and the Pentland Skerries during both the East and West setting tide. The location and extent of these may affect currents up to a few kilometres from the islands. In addition, a large anticlockwise eddy (the Liddel Eddy) forms between South Ronaldsay and Muckle Skerry on the East flowing stream and an eddy forms west of Lother Rock (the Lother Eddy) on the North West flowing tide (ebb tide). Eddies occur off South Walls and Switha in Orkney on the East flowing tide. Smaller and less consistent weak eddies are also found close to the shore along the Inner Sound of the Firth.

Tidal Races

Tidal races are found in a number of locations in the Firth. The largest is known as the Merry Men of Mey and, when fully formed, extends from St. John's Point on the Scottish mainland to Tor Ness on Hoy. The Merry Men of Mey race occurs during the west-going tidal stream, forming off of St John's Point at the start of the stream, extending across the Firth when the stream is at full strength and subsiding to mid-channel before disappearing at the start of the east-going tide.

Another notable tidal race occurs off the North end of Stroma and is named the Swilkie. The Swilkie persists almost continuously throughout the tidal cycle, and results from the interaction of the main tidal stream and eddies forming in the lee of Stroma. Races also form at the southern end of Stroma and on the northern and southern ends of Swona.

In the Inner Sound, a tidal race occurs off of the Ness of Huna and a larger race off the Ness Of Duncansby during the east-going stream. A smaller, shorter-lived race also occurs off the Ness of Duncansby during the West going stream.

Other tidal races occur between South Ronaldsay and Muckle Skerry on the east-going stream (as a result of the interaction between Liddel Eddy and the main tidal stream), south-west of Lother Rock on the west-going stream and off Brim Ness (Hoy) and Carrick Head (South Walls) in Orkney.

12.1.2 Water Depths at the Pentland Firth

The water depth in the Pentland Firth location is between 20 and 40 metres.

12.1.3 Exposure of Tidal Devices

The Pentland Firth can be subject to severe storms. This will have an effect on the water column and hence the loadings on the foundations and moorings. These loads need to be estimated in order to design the foundation or mooring.

12.2 Geology of the Location

As with many high tidal stream sites there is little seabed sediment and this will preclude certain types of foundations and moorings.

12.2.1 Bedrock

A high level review of geological information for the Pentland Firth provided by the British Geological Survey indicates that bedrock geology is dominated by Middle Devonian sedimentary deposits consisting of Old Red Sandstone and conglomerates.

Old Red Sandstone, in contrast to the typical formations of the Devonian, is largely a continental formation, laid down in freshwater and on land as a result of the erosion of the highlands of the Silurian period. This formation is extensive within much of Scotland and contains a large assemblage of well-preserved fossils, particularly of the Devonian fishes.

Within the Pentland Firth area strata is generally flat-lying which may dip towards the Atlantic Ocean to the west at approximately $5^{o.}$ Any loose sediment overlying Old Red Sandstone is likely to comprise of a thin layer of coarse sand and gravels washed through the Firth under the influence of strong tidal currents.

12.2.2 Seabed Sediment

It is likely that seabed sediment is thin and in parts, Old Red Sandstone may be exposed. This consolidated formation is expected to be relatively hard to drill or create piles into, although not as tough relative to igneous or metamorphic geological conditions.

In addition, the use of trenching techniques for a cable installation phase may not be possible, due to hard substrate. Further information concerning the thickness and type of sediment above the Old Red Sandstone is available from the British Geological Survey

12.3 Ecology and Marine Life at the Location

The location is in an area of abundant life.

12.3.1 General

The Orkney archipelago consists of at least 70 islands, 18 of which are inhabited throughout the year. In contrast, the northern Caithness coastline of approximately 135 km has a single island, Stroma, which is situated in the Pentland Firth. Tall cliffs, with only a few small intervening sections of sand and boulder beaches, dominate the remainder of the northern Caithness coastline. Saltmarsh is rare and largely restricted to small areas at the mouths of rivers and burns.

12.3.2 Fish

Fish species considered within the scope of this study included Blue Whiting, Norway Pout, Sole, Mackerel, Plaice and Nephrops, none of which had a sensitive life cycle stage occurring within the Pentland Firth.

12.3.3 Seabirds

Within the Pentland Firth long sections of the coastline support stacks and skerries, sandstone cliffs with horizontal bedding and glacial deposits comprising shingle or boulder beaches. Relatively short sections of sandy shore support locally impressive sand dune systems, including areas of species-rich coastal grassland. Communities of internationally important seabirds dominate the faunal interest of the coast: Auks (Guillemot, Puffin, Razorbill and Black Guillemot), Fulmar, Shag, Arctic Tern and Kittiwake, along with several large colonies of Storm Petrel. (Pollock et al., 2000) (Clunsten et al, 2001).

12.3.4 Coastal Birds

In winter, there are also important coastal populations of long-tailed duck and Great Northern Diver. A JNCC survey of Scapa Flow carried out in 1998/99 revealed 600 great northern divers, the highest wintering population anywhere in Europe. Internationally and nationally important shorebird populations, such as Turnstone, Purple Sandpiper and Ringed Plover, are present on beaches along this coastline (Pollock et al., 2000).

12.3.5 Sea Mammals

Within the sea surrounding Orkney, there are internationally important marine mammals including Otter, Cetaceans (whale and dolphin species) and 38% of the British Grey Seal and 25% of the Common Seal population. Orkney and the Shetland also have some of the largest percentages of the total UK population of Harbour Porpoise and Dolphins (Pollock et al., 2000).

12.3.6 Reptiles

There is also a population of Leatherback Turtle associated with the north east of the study area which enters Scottish waters at specific times of the year.

12.3.7 Near-shore

Near-shore environments, characterised by steep exposed rock faces and reefs of the outer coast, support areas of underwater kelp 'forest' which shelter a great diversity of other organisms. More sheltered coastal areas feature sandy or muddy seabed inhabited by burrowing animals such as Lugworms and Cockles. Sand also covers extensive areas of seabed offshore which is important for Sand Eels, a food source for fish species such as Cod, Haddock and Whiting. These fish, especially sand eels, provide essential food for seabirds and mammals. In more tide-swept conditions such Scapa Flow and areas around the south of Hoy, sand is often replaced by extensive Maerl beds, a UK Biodiversity Action Plan habitat (Foster-smith et al, 1993).

12.4 Marine Growth On Foundations and Moorings

There is likely to be marine growth on the foundations and moorings.

12.4.1 Introduction

The purpose of this review is to provide a description of the marine growth that might be expected to settle on foundations and moorings in the Pentland Firth. There is limited literature on the extent of marine bio-fouling on tidal devices and no information was available that could accurately predict the extent and types of fouling expected. The information below provides an overview of known fouling communities within UK waters and an estimation of the effect that it will have.

12.4.2 Marine Growth Overview

Subsea structures form artificial reefs which inevitably provide attachment and settlement sites for marine organisms, unless protected by substantial anti-fouling measures. Bacteria, algal spores and invertebrate larvae rapidly colonise submerged structures establishing a 'bio-fouling' assemblage (Wolfson et al., 1979).

The marine fouling community is formed by two distinct types of organism: 'soft' bodied organisms such as bacterial biofilms, algae, hydroids, anemones, soft coral, sea squirts and sponges; and 'hard' bodied organisms such as barnacles, tubeworms and mussels (Figure 12). The extent of marine growth colonisation entirely depends on the material of the subsea structure and the prevailing environmental conditions the structure is subject to.

12.4.3 Process of Marine Growth

The colonisation of a substratum is generally viewed as a four-stage process: biochemical conditioning of the surface, bacterial colonisation, diatom and protozoan colonisation, and settlement of larvae and spores (AUMS, 1980). This initial colonising population is described as the primary fouling community. The climax community is the final stage of ecological succession. In the case of marine bio-fouling, the climax community is described as the stable community of organisms including, but not limited to, mussels, barnacles, anemones and algae. Succession of organisms can be affected when climax communities are removed, for example by storms. If this occurs, primary communities will re-colonise the cleaned surface, and ecological succession will re-start.

Barnacles and hydroids are considered to part of the primary fouling community; therefore settlement occurs on relatively bare surface, after the biofilm has been established. Initial growth generally occurs rapidly, but slows as other communities of organisms and algae are established and therefore complete for space and/or food.

12.4.4 Factors Affecting Marine Growth

There are a number of factors that affects the pattern and extent of marine growth on subsea structures, including: depth of structure, temperature, food availability, competition and interactions with other organisms and environmental tolerances. As previously described, the Pentland Firth is influenced by strong tidal currents, leading to areas of turbulence and highly variable current speeds and directions. These unpredictable environmental conditions will therefore have an extremely strong influence on the extent and types of marine growth. Exposure of the surface results in reduced marine growth, and removal of settled organisms; and scour of surfaces from re-suspended sediments will affect the viability of fouling communities (Sell, 1992).

12.4.5 Mass of Marine Growth

Marine growth organisms (specifically hard organisms) contribute to the mass of the structure that they have settled on. Soft bodied organisms have a relative density equal to 1 (Table 24) as they are predominantly made of water. Hard bodied marine growth organisms comprising of a variety of materials for example calcium carbonate have relative densities ranging from 1.5 to 2.3. It is therefore possible to make an estimate calculation of the weight of marine growth on a structure upon completion of a marine growth survey.

Organism	Density Factor
Seaweed	1
Hydroids	1
Anemones	1
Soft Coral	1
Mussels	1.5
Tubeworms	2.3
Lophelia pertusa	1.8

Table 24 Density of Marine Growth

12.4.6 Marine Growth on Foundations

The foundation and body of the tidal device would generally be considered as any stationary part. The stationary surfaces would be expected to accumulate the majority of the marine growth organisms. Due to the high current velocities within the Pentland Firth, it is presumed that the marine growth would not form an extensive fouling layer, and that the type of organisms would be limited. Once the initial biofilm has been established, it would be expected that recruitment of organisms would consist of barnacles, tubeworms and mussels.

It is thought that the fouling community would remain as a primary community for an extensive period of time, due to the high speed currents and re-suspended particles sloughing off the fouling layers or creating a scenario in which organism larvae is unable to settle. Mussels are know to settle in multiple layers on stationary surfaces in calm waters, however, in the Pentland Firth, it would be expected that the mussel growth would be restricted, resulting in smaller mussels, and in single layers. Brown seaweeds (kelp – Alaria sp.) may eventually settle, but their growth would be restricted (potentially growing up to 1 metre maximum), and sea squirts (tunicates) may be able to settle under the body of the tidal device, depending on the current conditions.

12.4.7 Marine Growth on Mooring Ropes or Wires

The ropes or wires designed to anchor the floating tidal device to the seabed are potential surfaces for marine growth attachment, although it is unclear as to what will attach in areas of high current velocity like the Pentland Firth.

It is anticipated that there would be an initial fouling layer consisting of the green algae – Enteramorpha sp. and hydroids. Mussels are likely to grow on ropes or wires, and possibly abundantly, although probably not in multiple layers.

Other organisms such as anemones may settle on the ropes if the currents are not excessive, and again their growth is likely to be restricted.

12.4.8 Marine Growth on Rotating Blades

It is uncertain whether fouling organisms would be able to settle on the rotating and/or moving parts of the tidal device. The blades of the generators will turn for the majority of the tidal cycle, allowing seawater to pass through the housing unit, therefore providing a natural anti-fouling effect.

However, when the blades are stopped, organisms could settle in the form of Enteramorpha sp., barnacles and tubeworms. Tubeworms and barnacles are able to settle on surfaces when the water current is less than 2.57 m/s and green algae are able to settle when the water is less than 6.17 m/s. Another contributing factor is that the surface velocity of the blades will not be constant over the whole blade.

It may be suggested that the marine growth would occur in a thin layer, would be sparse over the blade surface and not likely to be consistent, however, it is impossible to predict. If these organisms are able to settle on the blades, then they are likely to have a significant impact.

12.4.9 Potential Problems

Unless protected by anti-fouling measures, any structure will become fouled. Excessive fouling can be problematic when:

- marine growth obscures the underlying structure and therefore impedes visual inspection;
- seaweeds may get entangled in the blades if they are able to establish in the housing unit, resulting in the blades being obstructed;
- erosion of the ropes/wires caused by marine growth or abrasion by re-suspended sediment particles may result in insecurity on stabilising ropes;
- marine growth may add significantly to the weight loading of the structure;
- attached organisms will increase the surface 'roughness' of the structure, therefore increasing the structure's resistance to water movement, resulting in greater hydrodynamic loading of the structure;
- marine growth contributes to increased corrosion due to mechanically disrupted surface coatings; and;
- micro-organisms and sulphate reducing bacteria damage steel and concrete and decomposing growth may yield acidic products which damage the underlying surface (AUMS, 1980).

In areas of high current velocity it would be expected that the overall marine growth would be reduced, however if the currents in the area are reduced or are less than anticipated, the pattern of marine growth may be different than described above.

In sheltered areas, or areas of lower current velocity, mussels may be able to grow in multiple layers, significantly adding to the mass of the device, the photic zone (the zone in which seaweeds are able to grow) would be lower in the water column, possible up to a depth of 25 m. From about 2 to 3 years after installation soft marine organisms may be able to settle including anemones and soft corals.

However it would be expected that the soft organisms would not create and blanket cover, but would instead create a mosaic pattern of growth with the mussels, although it is not possible to predict which organism would be dominant.

12.5 Anti-Fouling Solutions

A number of anti-fouling solutions are available to reduce the extent of marine bio-fouling of a submerged structure. A summary of anti-fouling methods which could potentially be used are detailed below:

- Anti-fouling paints which incorporate biocides that act as contact toxins on the paint's surface or dissolve into the boundary layer of seawater surrounding the protected surface, and are in sufficient concentration to repel, kill or impair the development of the potential fouling organisms. The majority of anti-fouling paints include copper compounds as the main biocidal agent, with other compounds as booster biocides. Self-polishing (or ablative) paints are sophisticated types of anti-fouling paint, where a copper acrylate polymer is typically used to provide long-life protection (up to circa 7 years) on the hulls of bulk carriers, tankers and other types of ship. The anti-fouling lifespan depends largely upon the rate at which the surface of the coating reacts with seawater to form a water-soluble layer. This water-soluble layer then gradually erodes ('polishes') as seawater moves across the surface. This polishing process sheds any attached fouling and exposes fresh biocide.

- Copper nickel alloy which is incorporated into sheathing (typically as a foil on a non-conducting backing), as granular or mesh coatings (over non-conducting backing), and as a structural material. 90/10 copper nickel alloy is normally used. On contact with seawater, a combination of copper corrosion product and slime-forming marine bacteria, diatoms and protozoa forms to provide a protective layer on the anti-fouled surface. This film works as a contact toxin and has self-polishing properties. Copper nickel could potentially provide a long-life solution;

- Non-toxic methods do not employ biocides, but make the surface unacceptable to the settling organisms by other means (e.g. by interfering with the adhesion of fouling organisms, or by removal by abrasion of settling organisms). Surface coatings include self-polishing paints which do not contain biocides and fouling release ('non-stick') coatings based on silicon elastomer technology. Information on the life-span of non-toxic methods is limited.

The main issues concerning marine growth and anti-fouling is the inspection and maintenance of the foundations, moorings and the device. Anti-fouling measures will need to be regularly inspected, maintained and cleaned (if applicable) to ensure effective and efficient operation.

12.6 Tidal Current Converter

The table below (Table 25) gives a conversion between m/s and knots and vice versa for the range of tidal currents expected at the sites.

m/s	Knots	Knots	m/s
0.0	0.00	0.0	0.00
0.2	0.39	0.4	0.21
0.4	0.78	0.8	0.41
0.6	1.17	1.2	0.62
0.8	1.55	1.6	0.82
1.0	1.94	2.0	1.03
1.2	2.33	2.4	1.23
1.4	2.72	2.8	1.44
1.6	3.11	3.2	1.64
1.8	3.50	3.6	1.85
2.0	3.89	4.0	2.06
2.2	4.27	4.4	2.26
2.4	4.66	4.8	2.47
2.6	5.05	5.2	2.67
2.8	5.44	5.6	2.88
3.0	5.83	6.0	3.08
3.2	6.22	6.4	3.29
3.4	6.61	6.8	3.50
3.6	6.99	7.2	3.70
3.8	7.38	7.6	3.91
4.0	7.77	8.0	4.11
4.2	8.16	8.4	4.32
4.4	8.55	8.8	4.52
4.6	8.94	9.2	4.73
4.8	9.33	9.6	4.93
5.0	9.72	10.0	5.14
5.2	10.10	10.4	5.35
5.4	10.49	10.8	5.55
5.6	10.88	11.2	5.76

Table 25 Tidal Current Converter (m/s <-> knots)

13 ANNEX C – ADDITIONAL INFORMATION ON COST MODELLING

13.1 Cost Variability

The methodology calculates energy costs per kWh base on a base case, bounded by an optimistic and a pessimistic assessment. The figures below (Figure 13 & Figure 14) show the variation for both the Foundations and the Moorings, normalised as before.

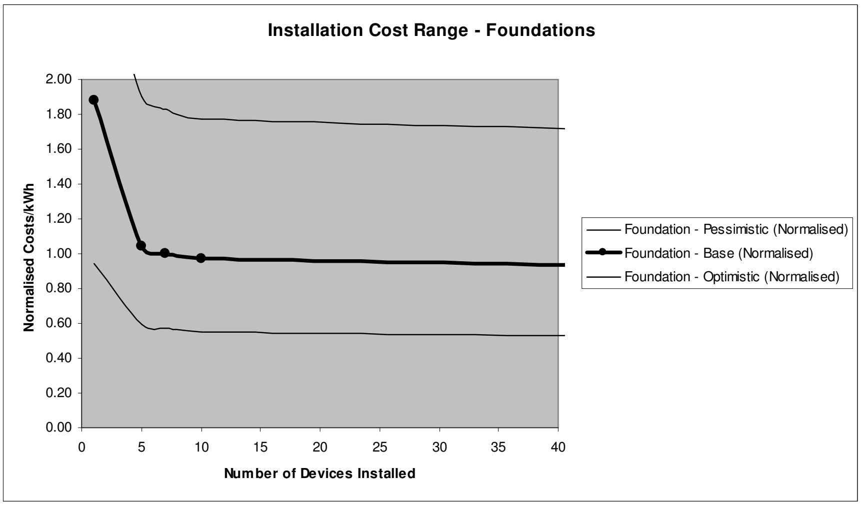


Figure 13 Normalised Installation Cost Variability - Foundations

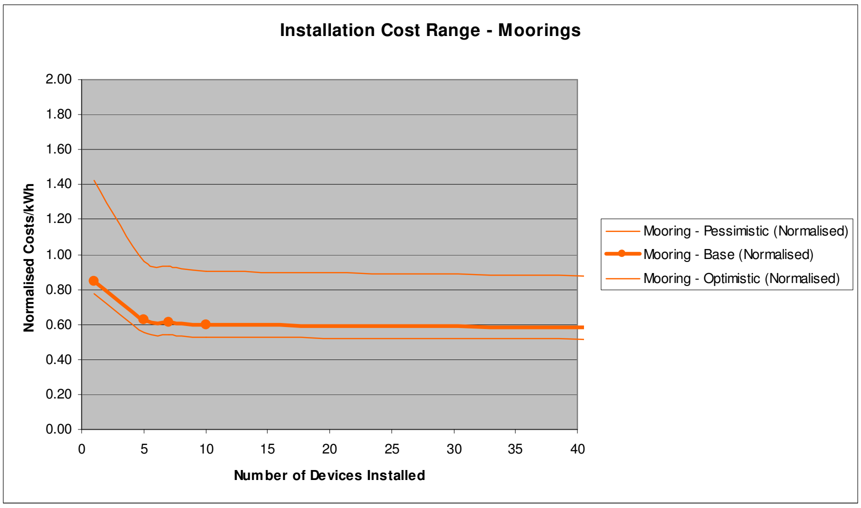


Figure 14 Normalised Installation Cost Variability - Moorings

13.2 Technical Parameters used in the Cost Model

The following technical parameters were used (Figure 15 & Figure 16):

Technical parameters - Foundations

				Pessimistic P	Base B	Optimistic O	Comment
P^Dev	Peak power for each device	Rated or peak power of the device conversion system, also the gross power before conversion losses, could be the rating of the generator.	kW	1,200	1,200	1,200	
P^Farm	Peak power for the farm	Rated or peak power of the farm conversion system, also the gross power before conversion losses. Could be the product of the number of devices in the farm and the peak power for each device.	kW	8,400	8,400	8,400	
P_Dev	Mean power device	Annual mean power of the device before conversion losses.	kW	480	480	480	Assumed capacity factor is 40%. However this is dependent on matching the power curve of the device to the tidal stream. It could be as low as 20 to 35%
		Capacity Factor		40%	40%	40%	
P_Farm	Mean power farm	Annual mean power of the farm before conversion losses.	kW	3,360	3,360	3,360	
Pi	Capacity installed for these cost levels	Assumed cumulative capacity installed by the time these costs are reached.	kW	0	0	0	This does not appear to be used in the calculations
Ni	Number of devices installed	Assumed cumulative number of devices installed by the time these costs are reached.	Devices	0	0	0	This does not appear to be used in the calculations
Nf	Number of farms installed	Assumed cumulative number of farms installed by the time these costs are reached.	Farms	0	0	0	This does not appear to be used in the calculations
ND	Number of devices in farm	Number of individual devices in farm, I.e. the scaleable part of the farm.	Devices	7	7	7	
Ds	Distance to shore	Distance to shore assumed, I.e. length of electrical connection.	km	0	0	0	This does not appear to be used in the calculations
Dm	Distance to routine repair base	Distance to dock where routine repairs undertaken or where service vessels are located.	km	0	0	0	This does not appear to be used in the calculations
E	Annual **farm** energy capture	Net annual energy delivered to point of connection to the electricity grid including all losses and downtime.	kWh/y	22,781,606	22,781,606	22,781,606	
L	Design life	The design life of the majority of the device. (Some subcomponents might have shorter lives, we are not interested initially in these).	years	20	20	20	Early adopted first generation technology is unlikely to have a design life of greater than 10 years due to obsolescence of technology
XL	Transmission efficiency	Efficiency of the farm to grid transmission system.		90%	90%	90%	
Av	Device availability	Time when device is available to generate whether wave climate is suitable or not, I.e. time when not being serviced, or broken.	%	86%	86%	86%	Mature offshore oil and gas installations achieve availability in the range 86% to 96%. It is unlikely that first generation technology will achieve better than oil and age mature technology.
							White - Data Entry Values
							Lavender - Interim Calculated Values
							Tan - Final Calculated Values
							Grey - Unused in this version

Figure 15 Technical Parameters - Foundations

Technical parameters - Moorings

				Pessimistic P	Base B	Optimistic O	Comment
P^Dev	Peak power for each device	Rated or peak power of the device conversion system, also the gross power before conversion losses, could be the rating of the generator.	kW	1,200	1,200	1,200	
P^Farm	Peak power for the farm	Rated or peak power of the farm conversion system, also the gross power before conversion losses. Could be the product of the number of devices in the farm and the peak power for each device.	kW	8,400	8,400	8,400	
P_Dev	Mean power device	Annual mean power of the device before conversion losses.	kW	480	480	480	Assumed capacity factor is 40%. However this is dependent on matching the power curve of the device to the tidal stream. It could be as low as 20 to 35%
		Capacity Factor		40%	40%	40%	
P_Farm	Mean power farm	Annual mean power of the farm before conversion losses.	kW	3,360	3,360	3,360	
Pi	Capacity installed for these cost levels	Assumed cumulative capacity installed by the time these costs are reached.	kW	0	0	0	This does not appear to be used in the calculations
Ni	Number of devices installed	Assumed cumulative number of devices installed by the time these costs are reached.	Devices	0	0	0	This does not appear to be used in the calculations
Nf	Number of farms installed	Assumed cumulative number of farms installed by the time these costs are reached.	Farms	0	0	0	This does not appear to be used in the calculations
ND	Number of devices in farm	Number of individual devices in farm, I.e. the scaleable part of the farm.	Devices	7	7	7	
Ds	Distance to shore	Distance to shore assumed, I.e. length of electrical connection.	km	0	0	0	This does not appear to be used in the calculations
Dm	Distance to routine repair base	Distance to dock where routine repairs undertaken or where service vessels are located.	km	0	0	0	This does not appear to be used in the calculations
E	Annual **farm** energy capture	Net annual energy delivered to point of connection to the electricity grid including all losses and downtime.	kWh/y	22,781,606	22,781,606	22,781,606	
L	Design life	The design life of the majority of the device. (Some subcomponents might have shorter lives, we are not interested initially in these).	years	20	20	20	Early adopted first generation technology is unlikely to have a design life of greater than 10 years due to obsolescence of technology
XL	Transmission efficiency	Efficiency of the farm to grid transmission system.		90%	90%	90%	
Av	Device availability	Time when device is available to generate whether wave climate is suitable or not, I.e. time when not being serviced, or broken.	%	86%	86%	86%	Mature offshore oil and gas installations achieve availability in the range 86% to 96%. It is unlikely that first generation technology will achieve better than oil and age mature technology.
							White - Data Entry Values
							Lavender - Interim Calculated Values
							Tan - Final Calculated Values
							Grey - Unused in this version

Figure 16 Technical Parameters - Moorings

13.3 Technical Parameters used in the Cost Model

The following cost parameters were used (Figure 17 & Figure 18). All costs are normalised with the capital cost of the foundation base case with 7 devices installed equal to 1.

Cost parameters - Foundations

				Pessimistic	Base	Optimistic	
				P	**B**	**O**	Comment
Cs	Structure	Cost of main structure.	£k	0	0	0	Device structure excluded from estimate
Cm	Foundations/moorings	Cost of all foundations, anchors or moorings.	£k	1	0	0	**Step 2 - Cost to procure foundation hardware**
		Cost of individual foundations, anchors or moorings	£k	0.105	0.070	0.040	
Ci	Control/instrument	Control and monitoring instruments.	£k	0	0	0	Control and monitoring excluded from estimate
Cpto	Power Take-off	Power Take-Off costs including all mechanical and electrical components.	£k	0	0	0	Power take off excluded from estimate
Cgc	Grid connection	Grid connection.	£k	0	0	0	Grid connection excluded from estimate
Cisv	Installation surveys	Surveys.	£k	0	0	0	**Step 1 - Cost to Survey Site** Note: Could be circa 4 times as expensive if a geophysical survey is required for a piled/drilled foundation
		Survey Mobilisation and Demobilisation Cost	£k	0.003516	0.003516	0.003516	
		Survey Cost Per Device Location	£k	0.002109	0.002109	0.002109	
Cis	Installation of structure	Installation of the structure (including hire of vessels).	£k	0	0	0	**Step 4 - Cost of installation of the device**
		Installation Mobilisation and Demobilisation Cost		0.070311	0.049218	0.024609	
		Installation Cost per Device		0.040429	0.028124	0.014062	
Cim	Installation of foundations/moori	Installation of the mooring (including hire of vessels).	£k	1	0	0	**Step 3 - Cost to install foundations or moorings**
		Installation Mobilisation and Demobilisation Cost		0.105	0.053	0.035	
		Installation Cost Per Foundation		0.088	0.027	0.015	
Cig	Installation of grid connection	Installation of the grid connection from farm to shore and onshore work (including hire of vessels).	£k	0	0	0	Grid connection excluded from estimate
Ccc	Commissioning	Commissioning of farm.	£k	0	0	0	Commissioning excluded from estimate
Co	Management and other	Management, insurance and other costs.	£k	0	0	0	Management excluded from the estimate
Ctotal	Capital cost: Total installed		£k	**1.83**	**1.00**	**0.56**	
Opm	Planned maintenance	Planned maintenance and inspection.	£k/annum	0	0	0	**Step 5 - Cost to maintain the Foundations/Mooring** Note: Concrete foundations require minimal maintenance
		Maintenance cost per device	£k/annum	0.000158	0.000105	0.000105	
Omc	Monitoring/Control	Monitoring/Control of energy production and condition monitoring.	£k/annum	0	0	0	Monitoring and control excluded from estimate
Our	Unscheduled repair	Unscheduled repair.	£k/annum	0	0	0	**Step 6 - Cost to repair the Foundations** Note: Concrete foundations require minimal repair
		Repair cost per foundation	£k/annum	0.000158	0.000105	0.000105	
Or	Rent	Rent, both land and sea.	£k/annum	0	0	0	Rent excluded from estimate
Oins	Insurance	Insurance.	£k/annum	0	0	0	Insurance excluded from estimate
Ototal	Operating costs: total annual		£k/annum	**0.002215**	**0.001477**	**0.001477**	
Dtotal	Total decommissioning costs	Incurred after project life has ended.	£k				Decommissioning excluded from the estimate

White - Data Entry Values
Lavender - Interim Calculated Values
Tan - Final Calculated Values
Grey - Unused in this version

Figure 17 Cost Parameters - Foundations

Cost parameters - Foundations

				Pessimistic	Base	Optimistic	
				P	**B**	**O**	Comment
Cs	Structure	Cost of main structure.	£k	0	0	0	Device structure excluded from estimate
Cm	Foundations/moorings	Cost of all foundations, anchors or moorings.	£k	0	0	0	**Step 2 - Cost to procure mooring hardware**
		Cost of individual foundations, anchors or moorings	£k	0.042	0.035	0.028	
Ci	Control/instrument	Control and monitoring instruments.	£k	0	0	0	Control and monitoring excluded from estimate
Cpto	Power Take-off	Power Take-Off costs including all mechanical and electrical components.	£k	0	0	0	Power take off excluded from estimate
Cgc	Grid connection	Grid connection.	£k	0	0	0	Grid connection excluded from estimate
Cisv	Installation surveys	Surveys.	£k	0	0	0	**Step 1 - Cost to Survey Site** Note: Could be circa 4 times as expensive if a geophysical survey is required for a piled/drilled foundation
		Survey Mobilisation and Demobilisation Cost		0.003516	0.003516	0.003516	
		Survey Cost Per Device Location		0.002109	0.002109	0.002109	
Cis	Installation of structure	Installation of the structure (including hire of vessels).	£k	0	0	0	**Step 4 - Cost of installation of the device**
		Installation Mobilisation and Demobilisation Cost		0.043944	0.014941	0.014941	
		Installation Cost per Device		0.019336	0.007910	0.007910	
Cim	Installation of foundations/moori	Installation of the mooring (including hire of vessels).	£k	0	0	0	**Step 3 - Cost to install moorings**
		Installation Mobilisation and Demobilisation Cost		0.035156	0.021093	0.021093	
		Installation Cost Per Mooring		0.020214	0.014941	0.012304	
Cig	Installation of grid connection	Installation of the grid connection from farm to shore and onshore work (including hire of vessels).	£k	0	0	0	Grid connection excluded from estimate
Ccc	Commissioning	Commissioning of farm.	£k	0	0	0	Commissioning excluded from estimate
Co	Management and other	Management, insurance and other costs.	£k	0	0	0	Management excluded from the estimate
Ctotal	Capital cost: Total installed		£k	**0.67**	**0.46**	**0.39**	
Opm	Planned maintenance	Planned maintenance and inspection.	£k/annum	0	0	0	**Step 5 - Cost to maintain the Mooring**
		Maintenance cost per device	£k/annum	0.002637	0.001758	0.001758	
Omc	Monitoring/Control	Monitoring/Control of energy production and condition monitoring.	£k/annum	0	0	0	Monitoring and control excluded from estimate
Our	Unscheduled repair	Unscheduled repair.	£k/annum	0	0	0	**Step 6 - Cost to repair the Moorings**
		Repair cost per mooring	£k/annum	0.003516	0.001758	0.001758	
Or	Rent	Rent, both land and sea.	£k/annum	0	0	0	Rent excluded from estimate
Oins	Insurance	Insurance.	£k/annum	0	0	0	Insurance excluded from estimate
Ototal	Operating costs: total annual		£k/annum	**0.043066**	**0.024609**	**0.024609**	
Dtotal	Total decommissioning costs	Incurred after project life has ended.	£k				Decommissioning excluded from the estimate

White - Data Entry Values
Lavender - Interim Calculated Values
Tan - Final Calculated Values
Grey - Unused in this version

Figure 18 Cost Parameters - Moorings

End.