Department of Mechanical and Aerospace Engineering

Flexible Moorings for Tidal Current Turbines

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Signed: Audrey Bowie Date: 7th September 2012

Abstract

Government subsidy is increasing the focus on renewable energy, within which tidal energy has the advantage of being both efficient and predictable. The UK is a world leader in this field, and has some of the most promising naturally occurring sites. The challenges of the underwater location and the distance of generation sites from the transmission network have thus far prevented effective ways of harnessing this energy source.

There is great variation in the concepts which are being developed and no industry standard approach has yet emerged. Tidal energy, despite its potential and conceptual promise has not yet been proved to be economically viable. The cost of tidal energy needs to be reduced to between 10 percent and 20 precent of its current cost to be fully competitive with traditional types of generation. Innovative next generation concepts show the most potential for being able to reach these targets in terms of simplicity, flexibility and cost.

Flexible moorings for tidal current turbines offer advantages in both installation and maintenance but require careful consideration in the design phase. Until the tidal energy sector builds up its own body of experience in flexible moorings, the best information is likely to come from other marine industries.

Respected international agencies have begun to extend their existing guidelines for design, maintenance and safety to the marine energy sector. These guidelines have many common themes but many differences of definition and standards. Reflecting pace of new technology and trends, the guidelines tend to focus on principles and encourage a case by case approach.

Elastomeric mooring tendons (widely used in the yachting and navigation buoy industries) have excellent properties allowing significantly greater compliance than traditional types of mooring line as well as potentially reduced costs and a maximisation of energy generation. They are not a panacea and their practicality and economic feasibility need to be evaluated on a case by case basis according to the particular circumstances and location.

Intrinsic uncertainties about the performance and lifetime upkeep of the elastomeric technology means that only experience will tell whether it is the best option for tidal current turbines.

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Contents

List of Figures

List of Tables

Glossary of Abbreviations

ABS - American Bureau of Shipping

API - American Petroleum Institute

DECC - Department for Energy and Climate Change

DNV - Det Norske Veritas

EMEC - European Marine Energy Centre

EU - European Union

FPS - Floating Production Systems

FPSO - Floating Production and Offloading Unit

FPU - Floating Production Unit

g(CO2)- Grams of Carbon Dioxide

HSE - Health and Safety Executive

IACS - International Association of Classification Societies

IALA - International Association of Marine Aids To Navigation and Lighthouse Authorities

MBS - Minimum Break Strength

MOU - Mobile Offshore Unit

NACA - National Advisory Committee for Aeronautics

NLB - Northern Lighthouse Board

NOAA - National Oceanic and Atmospheric Administration

REUK - Renewable energy United Kingdom

ROC - Renewables Obligation Certificate

ROV - Remotely Operated Vehicle

UK - United Kingdom

USA - United States of America

1 Introduction

Renewable energy is becoming ever more recognised as an extensive energy resource, with a global potential for providing sustainable energy to the world's consumers. Awareness of climate change and the depletion of fossil fuel reserves, provoking fluctuations in their costs, are prompting investors to consider renewable energy generation technologies as an appealing business proposition. The ability to generate the energy to be consumed domestically can ensure security of supply by reducing the need for imports of fuels and diversification of generation type.

Governments are pushing for growth in the industry with policies and incentive schemes to encourage developers and investors alike. The European Union (EU) have set a target of 20 percent reduction in carbon emissions and 20 percent of final energy consumption to be from renewable energy sources by 2020 (European Commission, 2012). Compulsory national targets are in place; member states can implement incentives to ensure that these targets are met.

The UK's target is to reach 15% energy production from renewable energy sources by 2020. However, the Scottish government have ambitious targets to reach 100% of the country's electricity consumption from renewable energy by 2020 (Scottish Executive, 2011). Whether or not this can be achieved will rely on the technology and infrastructure being available.

The main support incentive provided by the UK government for renewable technologies is in the form of Renewables Obligation Certificates, or ROCs. ROCs are awarded per MWh of electricity produced by renewable sources at present 3 ROCs are provided for each MWh generated from tidal energy and 5 ROCs are provided per MWh generated from wave energy in Scotland (DECC, 2012). Compared to onshore wind at 0.9 ROCs per MWH, it is evident from the difference in ROC value between technologies which areas the UK government are eager to develop. Electricity suppliers must "pay" 0.158 ROCs per 1MWh of electricity provided from non renewable sources to UK customers for the period 2012 - 2013. If the supplier has a shortfall of ROC's gained from the renewable sources against the ROCs paid for non renewable sources, they are required to pay a penalty of £40.71 per ROC for 2012 - 2013 (DECC, 2012). These bandings and cost of ROCs are under constant assessment and review to remain in line with developments and the economic climate.

The marine renewable energy industry has had increasing of attention in recent years as a result of all these factors. Development of new technologies is being pushed forward at high speed, in order to meet these targets, and in so doing, address supply and environmental issues. Wave and tidal energy converters are predicted to have around 6 g(CO2)/kWh emissions throughout their lifecycle. Compared with the most efficient type of fossil fuel energy generation, Combined Cycle Gas Turbines which produce 446 g(CO2)/kWh of emissions throughout their service life (DTI, 2005), marine energy converters are a significant improvement and can contribute greatly to proposed targets.

Tidal energy conversion is a great resource in the UK with an estimated “10 to 15% of the global harvestable tidal resource” (Johnstone, et al., 2012). Many consider the UK leaders in the development of tidal technology, with such substantial tidal resources, and the worlds only dedicated test centre for tidal energy converters, European Marine Energy Centre in Orkney which is a test ground for emerging concepts of tidal energy capture.

Unlike most other types of renewable energy; tidal energy is an accurately predictable resource. Wind and wave energy is stochastic and prediction relies on accurate weather predictions. Despite developments in forecasting techniques, is an art yet to be perfected, particularly in UK climates. In a future with an energy mix composed of a high proportion of stochastic generation, the predictable, although variable, energy supplied by tidal energy conversion will be able to provide a stable base load to the grid.

1.1 Aims

In an unsubsidised world, it is essential that the cost of tidal current energy must be economically competitive with traditional types of energy generation. For this to happen, the cost of tidal current energy must be reduced to less than 20 percent of its current cost. This thesis will set out to establish how the industry should approach the reduction of the cost of energy by:

- Identification of cost centres which could be reduced significantly.
- Assess existing marine energy experience which can be drawn upon for use in the development and implementation of tidal energy generation technology.
- Investigation of options for flexible moorings for tidal current turbines as an option to reduce costs and improve performance.
- Examine the functional and economic feasibility and requirements for the use of elastomeric mooring tendons in the moorings of tidal current turbines.

There is a lot of development ongoing to improve the performance and reduce the costs of tidal current turbines themselves. This thesis will look at how flexible moorings can seek to answer the question: “Can elastomeric mooring lines help towards the economic viability of tidal current energy generation?”

2 Tidal Stream Energy

Tidal current energy generation is a rapidly developing industry and the UK has an excellent resource which could go a long way to contribute to reaching government targets and supply a significant proportion of its energy consumption. The nature of the UK's resource lends itself well to tidal current energy generation in that it is an ever present, predictable and importantly sustainable resource. The harvesting of this energy is not without its challenges, which must be addressed in the development of generating technologies are to become successful.

2.1 Tides

Tides are a consequence of a complex combination of forces; however the key constituents affecting the tidal cycle are the gravitational forces of the moon and the sun acting on the Earth's oceans. These forces cause significant movement of the water in the oceans; it is this movement which holds a huge amount of energy.

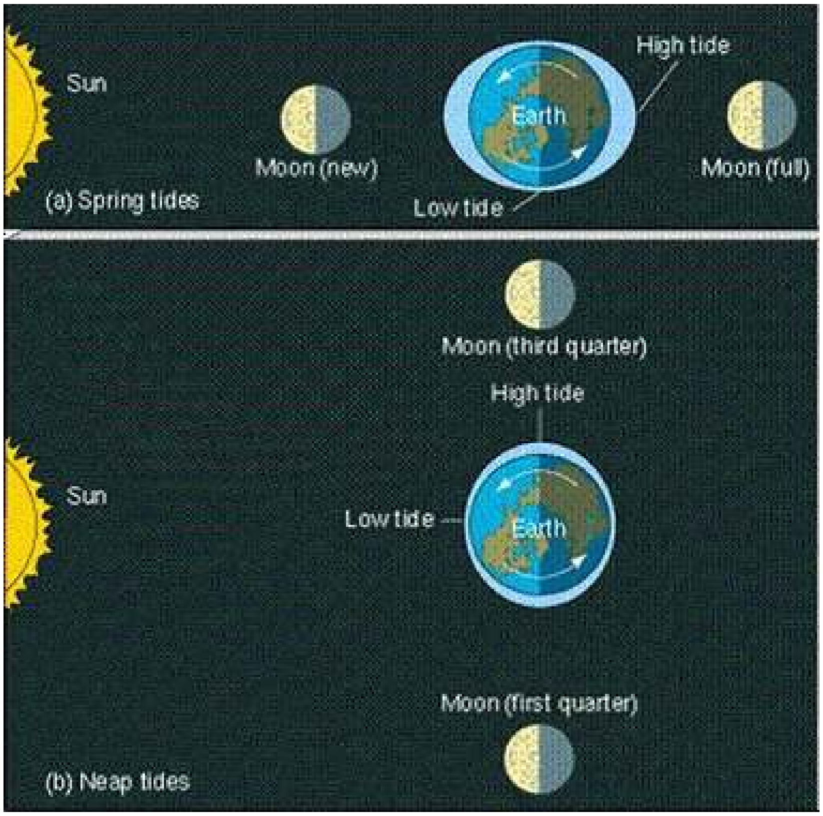


Figure 1 - Gravitational forces causing spring and neap tides (Leslie, 2012).

In any one location, there are two high tides and two low tides during one day; this is a semidiurnal tidal cycle. The time between two high tides is about 12 hours and 24 minutes (NOAA, 2004). The magnitudes of the affecting forces vary between spring and neap tides.

Spring tides see the largest tidal ranges throughout the tidal cycle, as illustrated in Figure 1, this is due to the linear alignment of the moon and the sun causing forces to be combined and cause greater bulges in the oceans.

Neap tides see the smallest tidal range which is due to opposing forces from the sun and moon which can be described as perpendicular alignment. The complete tidal cycle is from spring tide to neap tide and back to spring tide, and lasts about 14 days.

The tidal cycle for any given location can be theoretically approximated by a double sinusoidal function (Frankel, 2002). The resultant tidal velocity throughout the cycle is represented in Figure 2. The transition between slack tide (0 m/s velocity) and peak tidal velocity within the cycle are known as flood and ebb tides. The negative velocities in Figure 2 represent flood tides and ebb tides which flow at approximately 180° to each other.

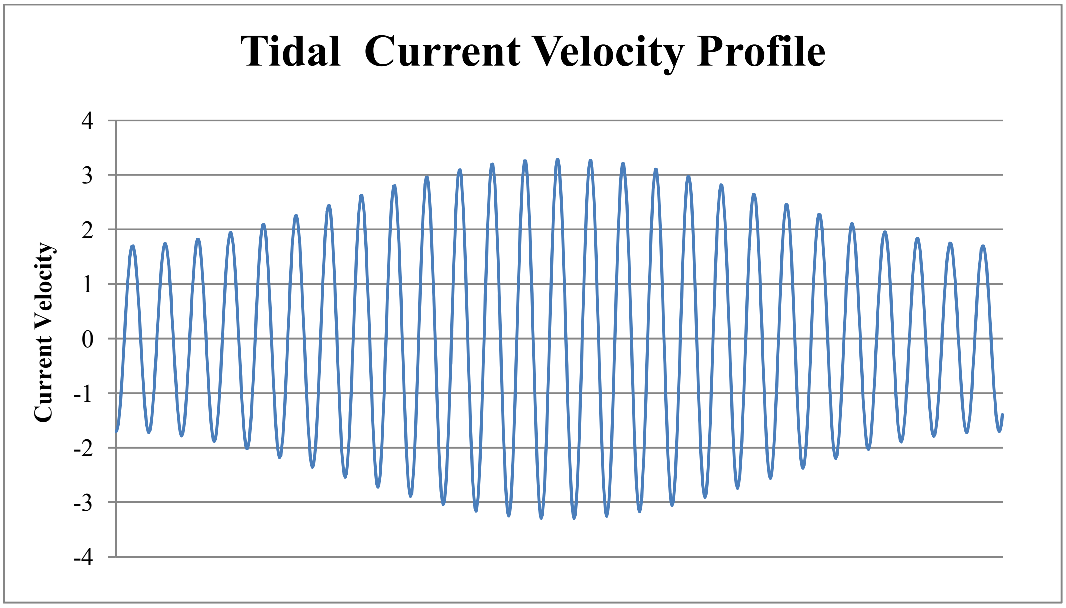


Figure 2 - Tidal current velocity profile

The tidal cycle causes a great deal of movement of water. There is significant variation of tidal fluctuation due to landmasses preventing free flow movement of this water. Where water is forced through relatively narrow channels, high volumes of water are forced to pass through the channel, creating high current velocities. The volume of water passing through the channel varies within each semidiurnal tidal cycle and similarly throughout the complete tidal cycle.

It is this passing of tidal flows which is where tidal stream energy conversion is most effective. The map in Figure 3 shows the sites around the UK where the velocity of tidal current is most concentrated.

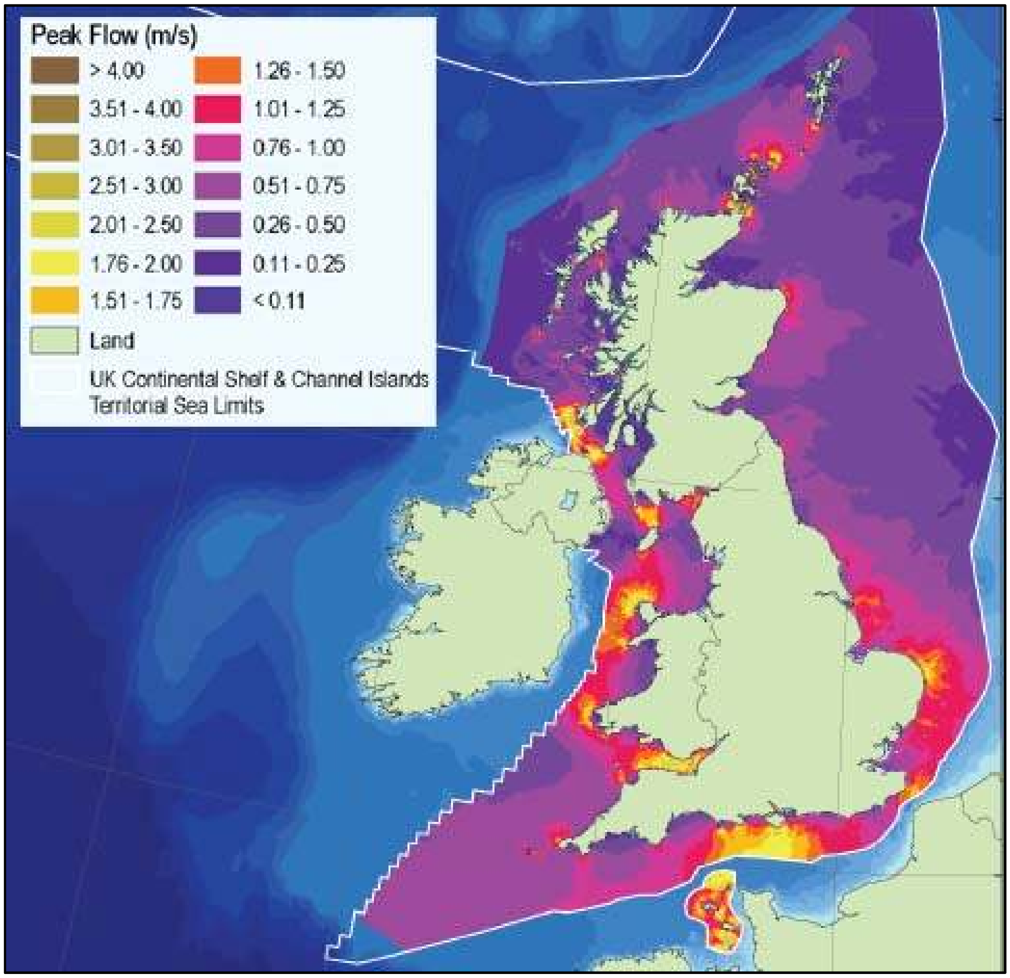


Figure 3 - Atlas of UK tidal energy resource (ABPmer, et al., 2004)

It is clear from this illustration that there are areas which have a highly concentrated flow rate. It is estimated that this could supply up to 30GW of electricity; 12 percent of the UK's current electricity consumption (DECC, 2012).

2.2 Challenges facing tidal stream energy

At present the industry consists predominantly of emerging technologies, with development and trials of a wide range of concepts taking place. There is not yet any specifically accepted design, and with the huge range of devices in development, it is hard to establish which devices will be implemented on a large scale. Tidal stream energy conversion is not without its challenges, which will need to be overcome if this resource is to be successfully exploited. The devices which are successful will need to be designed to overcome these challenges.

Installation of tidal steam devices is, by the nature of the resource, a difficult procedure. With only minutes of slack tide in each cycle, installation will have to be rapid and easy. The device must be able to generate electricity during both flow and ebb tides In addition access to, and maintenance of the device must be considered in the design process to maximise output and therefore economic viability. The harsh operating conditions which devices will encounter below the sea are certainly a challenge to developers. Devices will be subject to bio-fouling and corrosion, as well as large forces generated by currents and waves.

Connection of devices to electrical transmission lines and transformers underwater is no mean feat. In addition the UK will require considerable infrastructure development and improvement to transmit energy generated in potentially remote costal sites, which are currently not part of the high voltage transmission network. This development will likely cause cost and environmental concern from the public.

Capital investment is required to progress in the development of these new technologies. To ensure that tidal energy generation is economically viable, the costs must be reduced as far as possible. In addition, the financial crisis of recent years has certainly made funds available for investment more limited and provides further motivation for reducing the costs of tidal energy conversion.

The Challenge:

To develop solutions to allow the capture of tidal current energy resources in spite of the numerous hurdles which lie before it.

3 Tidal stream energy converters using flexible moorings

The Carbon Trust has recently undertaken research into methods for "Accelerating marine energy" (Carbon Trust, 2011) to investigate possibilities for rapid reduction of the costs of marine energy and to step up the pace of technology development in the industry. They have identified that the key to significantly reducing costs could be to implement new concepts of next generation devices. It is essential that tidal stream energy generation becomes competitive with other generation types.

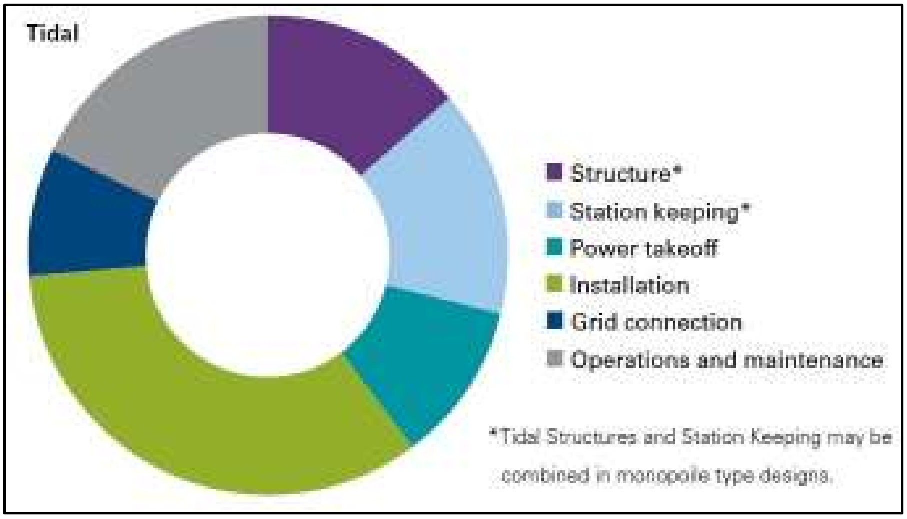


Figure 4 - Breakdown of cost centres for first generation tidal energy converter (Carbon Trust, 2011)

Figure 4 shows a breakdown of the cost centres for a typical first generation tidal energy converter. It is evident that the most considerable cost in first generation tidal energy conversion devices is installation. Furthermore, station keeping, structure and operations and maintenance cost centres make up significant costs within the total cost of energy. Economies of scale and experience will reduce these costs, but only to a limited extent. Innovative design and new concepts will be required to reduce the cost to a level which is competitive with traditional energy generation.

First generation concepts for tidal current turbines use piled foundations and existing technology, which has allowed them to be the forerunners in the industry at present. Next generation concepts could significantly reduce a range of costs including installation and maintenance by using flexible moorings instead of pile mountings for turbines (Clarke, et al., 2009).

3.1 Tidal

There are about eighty developers of marine current turbines (EMEC, 2012), these devices are in a range of stages of development from pre-build, design stages to operational deployment. Of these developers, about 1/8th use flexible moorings rather than piles or foundations. These developers are listed in Table 1.

Table 1 Marine Current Turbine Technologies Using Flexible Moorings.

Device	Developer	Development Status
Aquantis "C-plane"	Ecomerit Technologies	Development stages with nothing built (Ecomerit Technologies , 2011).
Aquascientific Turbine	Aquascientific	10kW prototype currently deployed (Aquascientific, 2010).
Bluetech	Bluewater	Building a prototype at present (Bluewater, 2011).
Sea Urchin	Elemental Energy Technology Limited	Testing of a small scale prototype is underway (Elemental Technologies Ltd., 2012).
DeepGreen Technology	Minesto	Successful sea trials completed and development of a 3MW array is underway (Minesto, 2012).
CoRMaT	Nautricity	Completed sea trials and is producing commercial scale devices (Nautricity, 2012).
Evopod	Ocean Flow Energy	Developing a 1/4th scale prototype following successful trials of their 1/10 scale prototype (Ocean Flow Energy, 2012).
SR250	Scot Renewables	Completed several scaled prototype testing and are continuing to model further scale models (Scot Renewables Tidal Power Ltd., 2012).
TidEL	SMD Hydrovision	1MW prototype is being developed (REUK, 2012).

As yet, none of the technologies are at commercial scale; however the majority of them have undergone successful trials of scaled prototypes, proving that the concepts work. Further development and testing of these devices will be required.

4 Why flexible moorings?

The number of developers opting for the flexibly moored option is testament to the benefits which they believe can be gained from this option. There are several aspects of the lifecycle of a tidal current turbine which can benefit from the use of flexible moorings. They are however, not without their issues, and a balance must be achieved between the pros and cons of using flexible mooring systems.

4.1 Pros

The majority of moored tidal current turbine developers agree that by using a flexibly moored system, the device will be automatically self aligning to the direction of current flow (Bluewater, 2011) (Minesto, 2012) (Nautricity, 2012) (Ocean Flow Energy, 2012) (Scotrenewables, 2011) (SMD Hydrovision, 2012). The direction of tidal flow reverses twice daily; by self-aligning, not only does this ensure that the device is orientated for maximisation of energy generation, it can eliminate the need for complex controls for electronic control of the orientation of the device and their associated cost and maintenance.

The installation of flexible moorings can provide significant cost reductions when compared with the installation of piles used for many of the first generation designs of tidal current turbines (Ocean Flow Energy, 2012) (Scotrenewables, 2011). The vessels required for the installation are relatively much simpler. Moreover, since the nature of the waters in which the turbines are to be installed have only short periods of slack tide, the installation of foundations and piles can become a very complex and long process taking several days, compared to as little as hours for installation of mooring systems.

Capital costs associated with high volumes of material and its manufacturing costs required for seabed mounted devices and piled foundation devices can be significantly reduced (Ocean Flow Energy, 2012) (Scotrenewables, 2011). Additionally, the overall weigh of the device can be reduced potentially making lifting and transportation of the device easier (REUK, 2012).

Many of the developers of flexible moored tidal current turbines state that one of the key features of the device on a moored system is the ease of attachment and removal of the device from the mooring (Minesto, 2012) (Ocean Flow Energy, 2012) (Scotrenewables, 2011) (REUK, 2012). This ensures that minimal maintenance has to be done offshore, and that the devices can be removed to land. By removing the device from its location, the time the vessels are occupied can be reduced. The maintenance then takes place on land which is logistically much simpler than offshore, and also provided improved safety of personnel carrying out the maintenance.

Compliant flexible moorings can provide improved survivability of the device (Scotrenewables, 2011) (Ocean Flow Energy, 2012) (Aquascientific, 2010). The devices will be subject to current and wave turbulence in their deployment locations, and the ability of the mooring system to allow the device to move with these forces rather than against them can improve the survivability prospects of the device; and therefore have the potential to reduce the inspection and maintenance requirements.

Tidal currents increase towards the surface of the water. By floating the device, it can be positioned near or on the surface of the water, increasing the potential energy available for conversion to electricity, unlike seabed mounted devices (Nautricity, 2012). By maximising the production of the device, its economic viability is improved.

Enabling deployment in deep water is a possible benefit of the flexibly moored device (Nautricity, 2012) (SMD Hydrovision, 2012). Installation of designs which require foundations and piles in deep water is potentially complex and expensive, or even impossible. Flexible mooring lines and anchors allow deployment in deeper water zones, where other designs may by impractical.

As well as logistical and functional benefits, the common factor in all of these benefits is that they have the potential to improve the economic viability of the designs.

4.2 Cons

Whilst the benefits of flexible mooring systems for tidal energy converters are widely publicised by developers, there is little talk in their documentation of the difficulties derived from the use of moorings rather than piled or gravity based systems.

Tidal energy converters must have an electrical connection to transmit the energy generated to the grid. Experience from the offshore wind industry can be applied to solid mountings; however flexible moorings pose this problem in a different light. The flexible mooring means that the electrical cables must also be able to flex in the same way as the mooring lines; copper conductors have an elastic elongation of only 0.5% (Alawa, et al., 2009). Damage to the conductor cables will surely damage the productivity of the device.

The mooring systems will have to support large loads; the design of the system must be specifically designed for the environment which it will be installed to ensure the safety and survivability of the device in the face of significant currents and turbulence. The reaction of the device and its mooring to fluctuations of velocity and direction of the tidal currents must also be considered. The device fouling the mooring is a potential issue with flexible mooring (Clarke, et al., 2008). However if this issue is considered in the design of the overall system then it may be avoided.

Bio-fouling and corrosion will certainly be factors affecting the device installed in harsh environments. The mooring system should not affect the function of the device, and certainly not cause inspection and maintenance requirements at frequencies any more that that of the device itself. Bio-fouling has the potential to cause increases in the loads on the mooring system if marine growth is significant, in fact the drag of the mooring lines, even without any bio-fouling must be considered in the loading of the system.

The procedure for the deployment of the mooring, its retrieval for inspection and maintenance, and the method of attachment and retrieval of the device must be thoroughly considered in the design of the system. Since the one of the principle benefits of the flexible mooring system over pile and gravity base installation is reductions in cost, deployment and retrieval of the mooring and device should also be cost effective and simple procedures.

The mooring should be designed to improve the performance and availability of the energy conversion device. If this can be achieved considering all the obstacles described, then flexible moorings provide a potential method of significantly reducing the cost of energy generated by tidal.

5 The costs of tidal energy conversion

There is great pressure on the marine energy industry to progress towards producing energy at costs which are competitive with traditional methods of electricity generation. At present the cost of tidal stream energy is between 29-33p/kWh (Carbon Trust, 2011). To be competitive with traditional generation methods; the cost of tidal current generation will have to drive towards the cost of the cheapest type of traditional energy source. This is combined cycle gas turbine generation which is predicted to cost between 2.5p/kWh and 5p/kWh, considering increases in fuel prices and cost of emissions (Carbon Trust, 2006). Since future fuel price rises are not known, there is potential for a large increase in the cost of fossil fuels; allowing cost competitiveness of renewable methods of electricity generation.

To achieve this cost reduction; the capital cost and operating costs of tidal current turbines must be reduced as far as possible, and the performance and availability of the device increased as far as possible. In the long term; the cost will be reduced by improving economies of scale. Gaining experience with the technologies as they develop will also help to reduce costs as safety factors can be reduced to the required level, rather than costly over engineering.

The two main costs during the life of a tidal current turbine can be defined as; capital cost and operating cost. Within these two areas the cost centres can be divided further as follows:

5.1 Capital cost

- Device components, manufacturing, and labour.
- Installation
- Station keeping
- Grid connection

Capital costs include all of the upfront costs prior to the device beginning its productive operation.

5.2 Operations costs

- Deployment and retrieval costs
- Overhauls
- Licenses and insurance
- Monitoring of device and performance

Flexible moorings, along with other benefits, can assist in reducing the capital and operating costs of tidal energy converters. Figure 5 shows a sample of the costs which are likely to be incurred during planned maintenance.

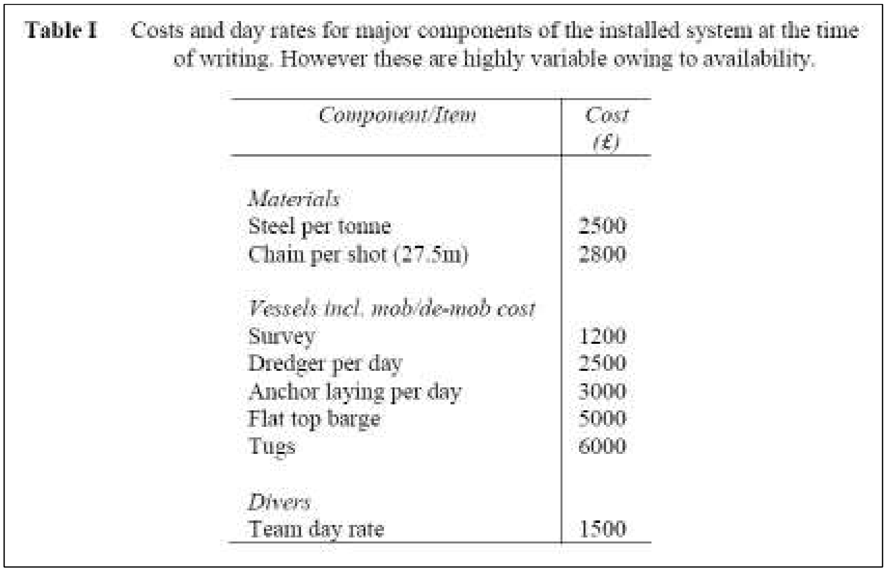


Table I Costs and day rates for major components of the installed system at the time of writing. However these are highly variable owing to availability.

Component/Item	*Cost (£)*
Materials	
Steel per tonne	2500
Chain per shot (27.5m)	2800
Vessels incl. mob/de-mob cost	
Survey	1200
Dredger per day	2500
Anchor laying per day	3000
Flat top barge	5000
Tugs	6000
Divers	
Team day rate	1500

Figure 5 Costs and day rates for major components of an installed mooring system (correct 02/2006) (Orme & Masters, 2006)

5.3 Maintenance costs

The aim of an effective maintenance strategy is to maximise the availability of the tidal energy converter. The key is to develop technologies which have a high reliability to maximise electricity production, this is, to increase as far as possible the proportion of time which the machine is in a state to be able to generate. Furthermore the maintenance schedule should seek to minimise unforeseen costs incurred by unplanned maintenance

Maintenance costs will vary significantly depending on whether it takes place in situ or onshore. Generally speaking maintenance onshore is much easier due to steady working conditions, good recourses, reduced requirements for vessels and improved safety for personnel.

5.3.1 Planned Maintenance

In a planned maintenance schedule, inspection will take place at pre-defined intervals. Upon each inspection it is decided if repair or replacement of any of the system components is required. Planned maintenance is defined prior to installation of the device. There are several methods for selecting inspection and maintenance schedule.

Time based approach: inspection is scheduled at pre-specified intervals. This approach can be applicable when there is experience of how the structure is affected by the environment at the location and the resulting degradation is known. For a system with little or no experience, this is unlikely to be the most suitable program for inspection.

Condition based approach: The condition of the system is assessed at each inspection. Depending on the level of wear and degradation, the time until the next inspection is required will be defined. This interval is likely to be the time until any of the components needs replacing.

Reliability centred maintenance: A probabilistic approach to maintenance is calculated according to statistical data on the historical failure rates of each component. This statistical approach may not consider equipment conditions at previous inspections. There is a possibility that the maintenance which is carried out does not match the requirements of the system as each location will have its own specific requirements. Error from this approach can occur in both excessive and inadequate maintenance, resulting in excessive costs for replacement, or unavailability and damages occurring from unpredicted system failure.

5.3.2 Unplanned Maintenance

Unplanned maintenance takes place in emergency situations. The costs of unplanned maintenance can be significantly higher due to availability of labour and personnel required for the maintenance; the costs of last minute requirements of resources is subject to premium charges. Unplanned maintenance will occur following a system failure, and therefore reduce the availability of the device to generate energy, losing income and incurring a secondary cost.

If, for example, a mooring line breaks it is also possible that damage could occur to the device, and/ or other devices. The costs incurred by this can also be significant. Additionally, unplanned maintenance requires that a stock of spare parts is available. This will incur costs in terms of both purchase and storage of there parts.

Broadly speaking, the aim of the planned maintenance schedule is to ensure that unplanned maintenance is not required. However it is not always possible to anticipate component failure and so unforeseen circumstances may occur.

5.3.3 Considerations for maintenance

In the process of planning a maintenance schedule, there are several aspects which must be considered (Davies, 2009).

The weather conditions which are needed for inspection and maintenance, this is an important factor for both safety and general accessibility. The sea state in terms of current flow velocity and wave characteristics must be appropriate to allow safe access to the system.

The duration of each procedure must be considered, whether it be the time taken to remove the device and take it ashore, or inspect and repair it in situ. The equipment, specialist vessels and workers must be considered in terms of availability. The marine operators will have requirements for inspection intervals and maintenance of devices. Additionally the procedures to be carried out must be risk assessed.

Each of these considerations are inter-related and the procedure as a whole must be well thought-out and planned to ensure an effective maintenance system.

6 Industry experience with mooring maintenance

With minimal experience in mooring of tidal energy converters, it is essential that the experience of other industries is drawn upon. The key industries with experience in mooring systems include; oil and gas, navigation buoys, and more recently floating offshore wind and wave energy conversion industries, the two later also having limited long term experience "There are still fewer than ten device-years of operational experience of tidal current devices at sea" (Mueller & Wallace, 2008).

Deployment of tidal devices for sea testing has to date provided short term experiences for the behaviour of the devices and their moorings. In a rapidly expanding industry, experience will accumulate at a high rate. In the mean time modelling will be used and experience from other industries will perform as a guide; however there is no substitute for practical experience.

6.1 Navigation buoys

Trinity house (Robinson, 2012) and the Northern Lighthouse Board (NLB) (Owen, 2012) both provided information about the maintenance of the moorings for their navigation buoys.

Both bodies use 38mm open link U2 150M19 steel chain (Owen, 2012) for their catenary mooring lines. The market cost of steel will affect the cost but at present 100m of chain will cost around £2500. These moorings are used to moor between 5 and 13 tonne steel spherical buoys.

Maintenance of the buoys is dependent on the environment of the buoy and the history of chain degradation in the past. NLB maintain their buoys annually or biennially, and Trinity House maintains their buoys every 1-3 years. The cost of the inspection for each buoy is nominally £1500 (Robinson, 2012).

The maintenance of the buoys and their moorings entails lifting them onboard the attending ship to be inspected. The full length of the chain is inspected and measured for wear down. NLB replace chain at a 25% wear down of the diameter of the chain links, while Trinity house replace the chain when it is worn, dependant on the environment 20% in more exposed areas and up to 30% in calmer areas.

NLB replace 10 meter sections of chain when they are worn. Trinity house replace the length of section depending on the wear down, for example the 25m section in the thrash zone of a 100m length mooring line. Occasionally the whole chain may need to be replaced where there is a longer length of wear or sections have previously been replaced. NLB state that the life span of the chain in the thrash zone is around 5 – 6 years. Trinity House also point out that the worst wear occurs in the nips of the chain links; this is the point where the links grind against each other. Other reasons for replacement of chain include distortion on degradation of links, however this is less common.

Whilst this information is useful for catenary moorings, its use for taut moorings is limited to inspection and maintenance methods, as well as the costs of maintenance.

6.2 Wave energy

The wave energy conversion industry’s leader in terms of experience is Ocean Power delivery’s Pelamis wave attenuator, with testing of its first full scale device taking place at EMEC in 2004 and the worlds first wave farm in 2008 in Portugal (Pelamis Wave Power, 2012). Now with eight years of experience, their experience is the most the marine energy industry has.

The majority of wave energy converters on flexible moorings use catenary moorings as a method of shock absorption from the potentially large waves from which it generates energy. There are a number of concepts in development which use taut moorings and these will also build experience as they undergo prototyping, testing and sea trials.

7 Mooring guidelines and regulations

Industrial experience can provide substantial resources for the requirements of, and procedures for mooring tidal current turbines. Table 2 lists the offshore standards and guidelines for a range of mooring applications which may be used as reference until the marine energy industry develops their own specific guidelines. Developing specific guidelines and regulations will require experience; however, some documents are being released already giving recommendations derived from industry standards and experience.

Table 2 Standards regarding mooring

Author	Title		Published	Applicable to
(Rawlings, 2010).	Mooring hardware specifications for marine energy converters		2010	Marine energy converters
ABS	Guidance notes on The Application of Fibre Rope for Offshore Mooring		March 2012	
API	API RP 2SK	Design and analysis of station keeping systems for floating structures	October 2005	Temporary and permanent moorings for floating structures
DNV	DNV-OS-E301	Position Mooring	October 2010	General, non industry specific guidelines
DNV	DNV-OS-E302	Offshore Mooring Chain	October 2008	Mooring of MOUs, FPUs, FPSO's
DNV	DNV-OS-E303	Offshore Mooring Fibre Ropes	October 2010	Mooring of FPSs, MOUs. Marine energy converters.
DNV	DNV-OS-E304	Offshore Mooring Steel Wire Ropes	April 2009	Mooring of MOU, FPUs, FPSOs.
DNV	DNV-OSS-312	Certification of Tidal and Wave Energy Converters	October 2008	Wave and tidal energy converters.
DNV and EMEC	Guidelines on design and operation of wave energy converters		May 2005	
EMEC	Guidelines for Marine Energy Converter Certification Schemes		2009	Marine energy converters

EMEC	Guidelines for Design Basis of Marine Energy Conversion Systems	2009	Marine energy converters
EMEC	Guidelines for Reliability, Maintainability and Survivability of Marine Energy Conversion Systems	2009	Marine energy converters
G L Noble Denton	Technical Policy Board - Guidelines for Moorings	December 2010	
HSE	Station Keeping	2002	
HSE	Floating production system – JIP FPS mooring integrity	2006	Mooring of FPSs.
HSE	Design and integrity management of mobile installation moorings	2004	
IACS	Guidelines for the Survey of Offshore Mooring Chain Cable in Use	October 2010	
IALA	No. 1066 - The Design of Floating Aid to Navigation Moorings	June 2010	Navigation buoys and structures
IALA	No. 1040 - The Maintenance of Buoys and Small Aids to Navigation Structures	May 2008	Navigation buoys and structures
Lloyds Register	Rules and Regulations for the Classification of a Floating Offshore Installation at a Fixed Location	April 2008	Permanent floating offshore installations.
Lloyds Register	Guidance on offshore wind farm certification - Design, build and operational requirements	April 2012	Offshore wind
Maritime and Coastguard Agency	Mooring, towing or hauling equipment on all vessels - safe installation and safe operation	November 2005	Vessels

The publication dates of these guidelines and regulations show that these documents are constantly revised to keep up to date with new technology, methods and trends. The majority of advice given in these documents is in the form of general principles rather than specific details. The main sentiment which runs through all of these documents is that design and maintenance should be decided on a case by case basis depending on the requirements of the system and its environment.

7.1 Mooring system guidelines

The following is a gives a sample of the guidance given in some of the key documents listed in Table 2.

Det Norske Veritas (DNV) is an independent body who provide technical and procedural requirements and recommended practice for the offshore industry including oil and gas and shipping. The aim of the standards provided by DNV is to "Safeguard life, property and the environment, at sea" (Det Norske Veritas, 2010).

With regards to moorings, their "Recommended practice for position mooring" provides recommendations for load requirements, system analysis, equipment selection, monitoring, testing and classification of mooring systems. These recommendations classify long term mooring as longer than 5 years (Det Norske Veritas, 2010), applicable to the mooring conditions for tidal current turbines. Fatigue should also be considered in the design of the system.

Furthermore more specific recommendations on mooring line types DNV have produced standards for Chain (DNV-OS-E302), Fibre ropes (DNV-OS-E303) and steel wire ropes (DNV-OS-E304). These specifications do not include recommendations for the inspection intervals or the expected life cycles of the mooring lines. They do include criteria for standards which should be maintained during manufacture. If there is an assurance that there is limited chance of mooring line defects arising from manufacture, then this reason for the unpredicted breakage of the mooring system is likely to be reduced, and therefore is necessary, and worth being adhered to.

In terms of maintenance of chain mooring lines, it is recommended that repair and replacement is carried out; depending on the corrosion and wear which has taken place. The resulting reduction in diameter of the chain links should be assessed and replaced if it has reached the limit of reduction or is deemed to be likely to reach that point by the time of the next inspection. It is possible that the inspection criteria will be defined following experience in specific locations and the normal rate of wear is established. Until this point it is likely that there will be more frequent inspections.

These general mooring standards, although general, are more directed towards floating units such as floating production units and floating drilling units. More recently DNV have also developed criteria for "Certification of Tidal and Wave energy Converters". This documentation demands that annual surveys entailing general inspection of easily accessible areas should take place, and that at five year intervals, close inspection of the whole system should take place. It also specifies that the survey plan should be completed before installation of the device and its mooring (Det Norske Veritas, 2005). This criterion is designed to allow the continuation of certification of the device, and is likely to be done in parallel with the maintenance program of the operator. It is, however, unclear whether this is the expected inspection interval of the operator and whether or not the operator should be carrying out additional inspection surveys. DNV work with the operator at the certification stages to ensure that an adequate inspection and maintenance schedule are planned.

The (American Petroleum Institute, 2005) have produced "Design and Analysis of station Keeping Systems for Floating Structures" to provide standardised procedures for design, analysis and evaluation of mooring systems for floating structures. The recommendations include guidelines on mooring system construction options, environmental, strength and fatigue considerations, and recommendations for design considerations including line length and tension, as well as equipment selection. Permanent moorings are classed in this document as having a design life in excess of 10 years. It suggests that inspection of permanent moorings can be expensive and that divers or ROV's should be used for inspection. However since the scales of the floating structures described in this document are significantly larger than tidal current turbines are likely to be, then this information may not be correct. For a design life of over 20 years, a 100 year storm criteria should be used. Design criteria such as those listed in Table 3 give an indication of the type of guidance provided.

Table 3 - Tension limits and safety factors for Quasi-static analysis of mooring lines (American Petroleum Institute, 2005)

	Tension Limit (% MBS)	Equivalent Factor of Safety
Intact	50	2.0
Damaged	70	1.43

Further guidelines include that the fatigue life should be 3 times that of the design life of the mooring system. Chain diameter should be increased by 0.2 – 0.4mm per year of intended design life for the thrash and splash zone, and 0.1 – 0.2mm in the other zones. This document gives no indication of the required mooring inspection times.

Lloyds Register provides classification services for all types of marine uses. It is recognised by several governments including the UK for providing statutory requirements for classification of offshore equipment, including new technologies and assessing their compliance with their existing recommended practices, as well as fitness for purpose (Lloyds Register, 2008). The document states that the interval for inspection must be agreed by LR in the planning stages. To maintain classification this pre-planned inspection schedule must be adhered to. The unit must also be inspected by a LR representative upon completion of inspection to ensure it meets the standards for initial classification. Re-installation may also require further inspection. Where possible; LR requires that the mooring system is subject to dry survey, however they are willing to consider alternative methods if suitable.

From this brief summary of the guidance provided by these documents, it is clear that each design, its components and capacities should be decided on a case by case basis. These regulatory bodies will work with the operator to ensure that a safe and adequate mooring is designed and that the inspection and maintenance procedures and schedules are established before the installation of the system.

A small number of documents have been produced specifically for the marine energy industry, but these follow a similar pattern to that of the general marine industry guidelines. Again a case by case design basis is required.

7.2 Mooring maintenance guidelines

The majority of these documents specify that an adequate maintenance schedule should be designed in advance of the installation of a device. Most do not give further detail on intervals. Without experience on specific components in specific environments, an iterative process could be used whereby the inspection intervals should be determined by the degradation of mooring components since the last inspection. For this approach to be reliable, careful documentation of each inspection should be recorded. This type of guidance comes from documents including (Health and Safety Executive, 2002), (GL Noble Denton, 2010), (IALA, 2008) (IALA, 2010)

Documents which include more specific details on suggested maintenance include the International Association of Classification Societies (IACS, 2010), who specify annual inspections. They also specify that every 5 years, there should be a more detailed, probably dry inspection of the mooring. This information relates directly to chains. This agrees with the recommendations of the DNV guidance on design and operation of wave energy converters.

There is a huge amount of information available about chain moorings. This is due to its extensive and long running use in the marine industry. Technology developments are providing other options for mooring lines, but as of yet there seems to be little of this information available in the public domain.

To summarise, it seems most likely that basic inspection of the moorings should be undertaken annually. Every 5 years a more detailed survey should be carried out including removal of the mooring system from the sea and dry inspection. Detailed recordings of the conditions of the system should be taken at each inspection interval. As such a time comes that experience is gathered, the inspection interval may be able to be increased.

8 Mooring systems

Selection of a suitable mooring system is vital for the survival and station keeping of a device. There are several components of the system which must be selected to compose a good mooring system. These include; configuration, anchorage, line type. There are several criteria which influence the selection of a mooring system including the forces which the system will have to withstand from currents, waves and wind and the weight of the structure itself. The depth in which the structure is to be moored must also be considered along with the duration which the mooring will be in service for.

8.1 Mooring function

Although mooring systems for marine energy converters may be seen as a secondary consideration after the actual device; they are in fact integral to the function of the system. The mooring serves an essential function within the conversion of marine energy to electricity.

8.1.1 Station keeping

The primary function of the mooring is to provide station keeping of the device. This mooring must be designed to ensure station keeping in both average and extreme environmental conditions. Keeping the device in a given location is vital to ensure that it remains in close proximity to the electrical connection; and does not strain it. The device must remain in the same position so that it can be located for inspection, maintenance and retrieval and that its location can be known to other marine users so that they are not obstructed by it. The device will most likely be situated within an array of devices; excursion from its intended position should be minimised to avoid collision with other devices within the array.

8.1.2 Compliance

A requirement of the mooring may be to allow compliance of the device within its environment. The ability to flex with the environment is important for many of the designs of tidal devices with flexible moorings since compliant moorings have a natural response to the flows of tidal currents (Mueller & Wallace, 2008). In a compliant system, the device is allowed the freedom of movement to orientate itself with respect to the flow of current, waves and wind to minimise damage to the device from the elements, and therefore improve the survivability of the device. A compliant mooring system can also aid in maximising the output of the device. Several of the developers of marine energy converters utilising flexible moorings state that this is one of the major benefits of the system and can avoid the need for expensive controls to optimally align the device with the environmental loadings.

8.2 Mooring Configurations

The two key divisions of mooring configurations are single point moorings and spread moorings. Each option has key functions which determine their suitability for the application at hand. There are two main line configurations which can be applied to both the single point and spread mooring configurations. These are catenary and taut mooring lines.

8.2.1 Single point mooring

In a single point mooring system, the mooring lines meet at a single point which is connected to the floating object. This set up is required if the object is to be allowed to weathervane around the point of mooring. This method is often used in order to minimise environmental loading on the object. There are many configurations of single point mooring systems which all perform this function.

8.2.2 Spread mooring

A spread mooring has multiple lines which generally meet the floating object at multiple points. This configuration ensures that the object retains a fixed heading or orientation. The alignment of the object should be decided according to the most frequently occurring direction of the environment, for example in line with typical wind direction or current.

8.2.3 Catenary mooring

There is extensive experience with this type of mooring system. In a catenary mooring, the line(s) approach the seabed horizontally before they reach the connection with the anchor; this ensures that the forces on the anchor are horizontal and the weight of the line provides the majority of the restoring force for station keeping. This mooring system allows a degree of elasticity in the system and so may improve the survivability of the device (Scotrenewables, 2011). The system can allow a freedom of movement as the loading on the mooring causes sections of the mooring line to rise and fall from the seabed (this section is known as the thrash zone). A diagram of a catenary mooring arrangement can be seen in Figure 6.

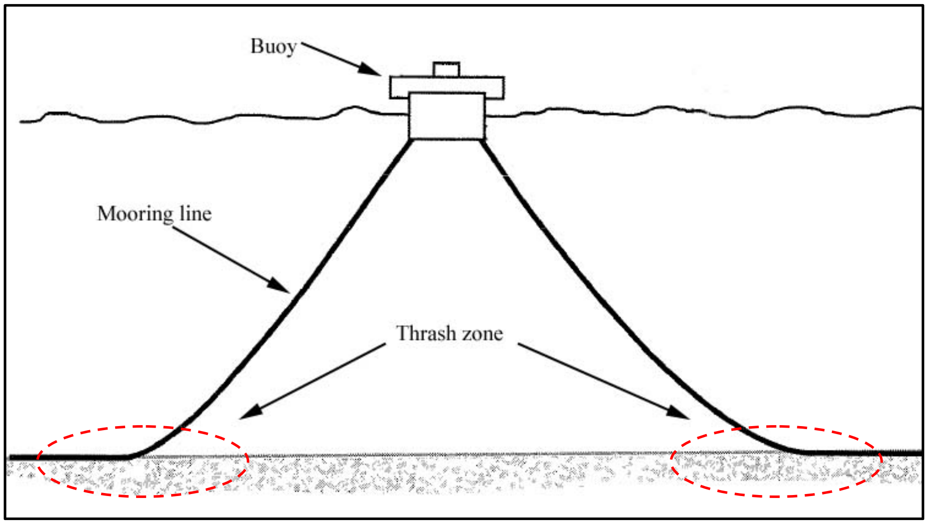


Figure 6 - Catenary mooring thrash zone

8.2.4 Taut mooring

The mooring lines arrive at the seabed at an angle, and do not make contact with the seabed. The loadings on the anchor are therefore both horizontal and vertical. The restoring forces in this type of system are generally provided by the elasticity of the lines; where the elasticity is dependant on the line material and type. Taut moorings can be used to minimise the excursion of the floating object comparatively to a catenary mooring system. Taut moorings are relatively new to industry, and are used more for deep water moorings to minimise excursion (Noble Denton Europe Limited, 2006). The avoidance of contact with the seabed of the taut mooring system has further benefits; the mooring line does not damage the seabed, and the seabed does not damage the line. This benefits both environmental concerns and maintenance requirements of the line. A diagram of a taut mooing arrangement can be seen in Figure 7.

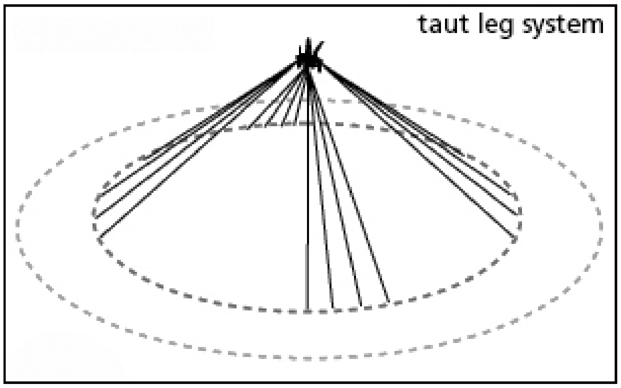


Figure 7 - Taut leg mooring construction (Offshore Moorings, 2006)

The considerations for the selection of taut or catenary mooring line depend mainly on the requirements of the floating structure. Taut moorings are more suited to highly accurate position keeping and allow only as much compliance as is allowed by the elongation of the mooring lines. In locations where rough environmental loadings are an occurrence, catenary mooring configurations allow compliance to reduce damage to the floating structure.

8.3 Anchor types

The anchor type selected for a mooring configuration will depend on several factors including; sea bed type and inclination, and loading characteristics. Anchor types vary greatly on load resisting characteristics as well as installation and retrieval methods and cost.

8.3.1 Drag embedment anchors

These anchors fix their position by penetrating the seabed by means of dragging. There are a wide range of shapes, sizes and weights available. They are able to resist very large loads in the horizontal plane and are therefore unsuitable for use with taut mooring lines. As with catenary mooring lines, there is a wealth of experience in their use. They can be deployed and retrieved many times and are often the mooring equipment provided on vessels.

8.3.2 Pile anchor

Pile anchors are composed of hollow tubes which are drilled or hammered into the seabed and can be grouted into position. The resistance comes from friction with the seabed material and the horizontal resistance of the seabed. Piles often have to penetrate deeply into the seabed to obtain the required load capacity, in both horizontal and vertical loading. “Anchor piles are characterized by being relatively long and slender and having a length to diameter or width ratio generally greater than 10.” (Davies, 2009)

8.3.3 Suction pile anchor

Similar in form to pile anchors, suction pile anchors are hollow tubes where suction to reduce the internal pressure of the pipe is used to create a pressure gradient which sucks the pile into the seabed to achieve the desired depth, and the pressure difference is maintained for the duration of its deployment. One of the benefits of suction pile anchors is that they can be removed by simply releasing the seal and returning the internal pressure to that of outside, releasing the pile. “Suction anchor piles are characterized by having a large diameter and a length to diameter ratio generally less than 8” (Davies, 2009)

8.3.4 Deadweight anchors

Also known as gravity anchors, these anchors use their own weight and friction with the seabed to generate station keeping ability. Deadweight anchors are generally made form concrete or steel (Vryhof Anchors BV, 2010), and to produce the required load resistance may have to be very large. They are the simplest type of anchorage; however load resistance is primarily vertical, with horizontal resistance being less reliable.

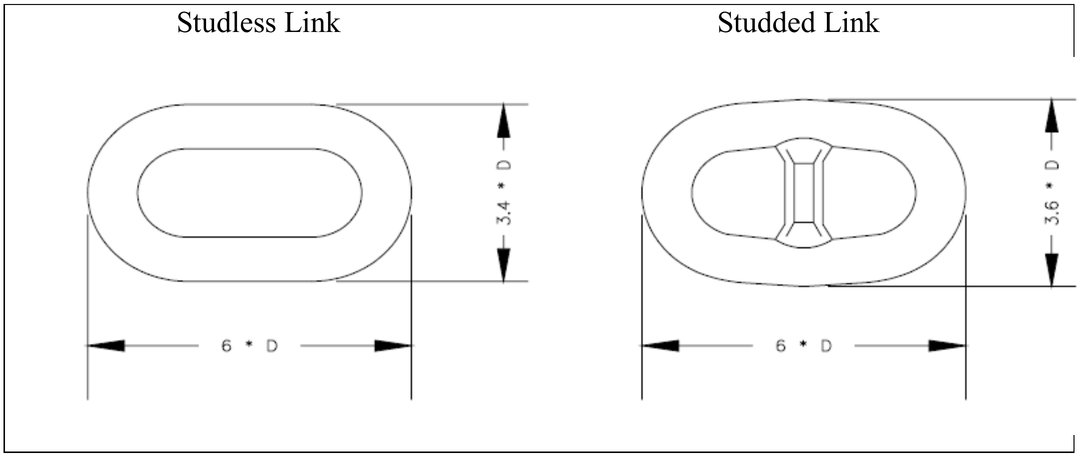
The selection of anchor will depend on the duration in that location. For short term moorings; drag embedment anchors are more suitable than the other options as they are easier to deploy and retrieve. The decision will also depend on the seabed type and incline. The loading on the anchor is a key consideration, the angle and size of the load will help to determine which anchor type is most suitable. For vertical loads, drag embedment anchors are less suitable whilst of horizontal loads dead weight anchors are less suitable due to likelihood of slipping.

8.4 Line Types

Mooring line selection is dependent on many factors. The type of line will determine how the system functions, as the elasticity of the line varies greatly with material selection.

8.4.1 Chain

There is a long history of the use of chains as mooring lines. This wealth of experience can help to reduce capital costs be reducing costly safety factors required for materials with less experience. Chains are most commonly made from steel of varying grades including those defined by the International Association of Classification Society for offshore mooring chain; R3, R3S, R4, R4S and R5, which should be selected depending on the load characteristics which they will be required to withstand. Chain links can be divided into two general groups of studded and studless links, which can be seen in Figure 8.



Studless Link

Studded Link

Figure 8 - Geometry of Modern Studded and Studless Chain (Health and Safety Executive, 2002)

Studded link chains are preferable in terms of ease of handling and are considered to have a higher reliability than studless link chains; however the fatigue life can decrease significantly with loose or broken links. The links require additional inspection of stud connection or welding.

Studless links avoid issues relating to loose or missing studs which can reduce maintenance and inspection costs, and can also reduce the line weight by up about

10% (Rawlings & Klaptocz, 2010) however the fatigue life can be comparable to half that of a studded chain.

Technical requirements and guidance for the design, materials, manufacture and testing of mooring chains are given by DNV-OS-E302, (Det Norske Veritas, 2008)

Steel chain in an ocean environment will be subject to corrosion. In addition the use of chain in a catenary mooring construction will involve a large amount of scour and abrasion, particularly in the thrash zone.

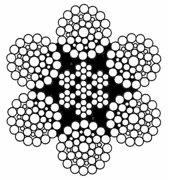
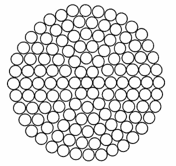
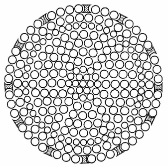
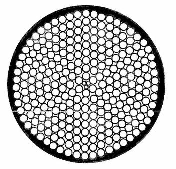
The selection of the length of chain is an important decision to ensure that it serves its function. The chain length and size will depend on the size of the load which it is mooring, this includes tidal and wave forces and the weight of the floating structure to be moored and the nature of the seabed. The length of chain will also depend on the depth of water and the tidal range in the location, the length will typically vary between 3 and 7 time s the water depth (Robinson, 2012) to ensure that the required compliance is provided by the mooring system.

8.4.2 Steel wire ropes

Wire ropes come in many different compositions. The general categories are multiple strands (generally 6 or 8), and spiral strand. In multiple strand wires, the strands are wound around the core in the same direction, whilst the spiral strands are wound around the core in different directions. The ropes can be covered with a sheath, to help prevent corrosion of the strands.

Multiple strand ropes are cheaper than spiral strand and have a greater elasticity however are more susceptible to corrosion. Spiral strand ropes generally have a higher strength and fatigue resistance; in addition, one of the benefits of spiral strand ropes is that they do not generate torsion forces as loads increase, as is the case with multiple strand ropes, and so are preferable in permanent moorings. Zinc fillers, which are smaller diameter strands which fit between the steel strands, can be used to further limit corrosion resistance.

Table 4 - Wire rope constructions and life expectancy (American Petroleum Institute, 2005)

	Wire rope construction	Life expectancy
	Galvanised 6- strand.	6-8 years
	Galvanised unjacketed spiral strand.	10-12 years
	Galvanised unjacketed spiral strand with zinc filler wires.	15-17 years
	Galvanised jacketed spiral strand.	20-25 years
-	Galvanised jacketed spiral strand with zinc filler wires.	30-35 years

Both API (American Petroleum Institute, 2005) and DNV (Det Norske Veritas, 2009) recommend a termination of a wire rope should use resin to pour the sockets, which can be fitted with bend stiffeners to avoid kinking at the join, particularly during installation. Wire ropes are unsuitable for catenary mooring lines since they are subject to kinking which can seriously damage their load capacity.

8.4.3 Synthetic fibre ropes

Synthetic fibre ropes have seen a significant increase since the expansion of deep water mooring and results of testing on these relatively new applications are becoming available (Noble Denton Europe Limited, 2006). This is particularly since lighter weight mooring lines lend themselves to this application.

Fibre ropes should not make contact with the seabed. They are therefore suitable for taut line applications as well as segments of a combination steel/ fibre rope system.

They can offer superior elongation properties for compliance of the mooring system than that of chain and wire ropes. One of the major differences from chain and wire rope is that fibre ropes display non-linear stiffness. Fibre rope moorings can provide elasticity for compliance; however this is limited to 8-10% (Paul & Irish, 1998).

There are several different materials which can be used for mooring lines; each has properties which should be considered in the selection of the most suitable rope for the mooring system. The most commonly used materials include:

- Polyester (polyethylene terephthalate)
- Aramid (aromatic polyamide),
- HMPE (high modulus polyethylene)
- Nylon (polyamide)

Some of the most common compositions of ropes are listed in Figure 9.

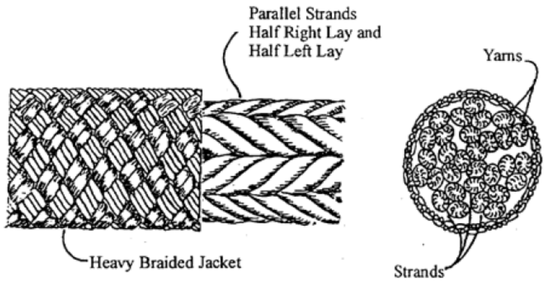
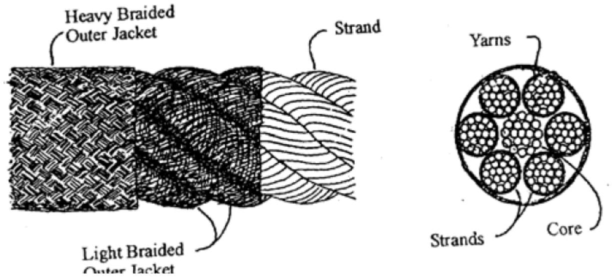
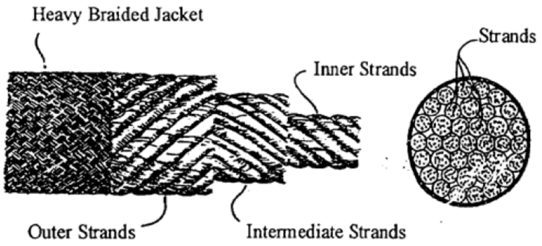
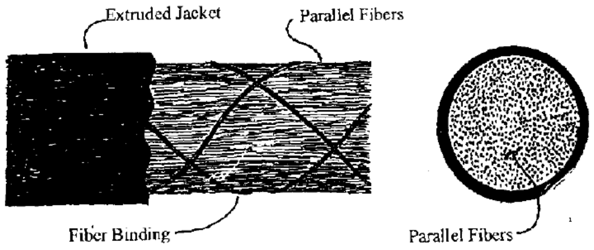
	
Parallel-Subrope rope.	Six-Strand rope.
	
Thirty-Six-Strand rope.	Parallel-yarn rope.

Figure 9 Typical compositions of fibre ropes (Det Norske Veritas, 2010)

As with steel wire rope, fibre rope can come in a range of compositions. Some of the rope compositions come with a jacket; this serves the function of protecting the load bearing inner fibres from marine growth, fish bites and general abrasion.

8.4.4 Elastomeric tension members

The key feature of an elastomeric tension member is that its elongation under load is significantly higher than the elongation of its traditional counterparts; chain, wire rope and even fibre rope. In the past catenary chain moorings have been used to allow compliance of the floating object. Elastic moorings can provide can provide significantly greater compliance, up to 400% elongation (Datawell, 2011), supporting the survivability of the device against tides, currents and waves.

The lighthouse authority includes fully elastic mooring lines in their guideline documents for both the design of navigation buoys (IALA, 2010), and guidelines on synthetic mooring lines (IALA, 2005). These documents suggest that the mooring line is selected by the appropriate length, diameter of cord and hardness of the rubber used.

There are a range of further benefits which can be achieved from elastic mooring lines. In other mooring systems, when the line loses tension due to turbulence in the water, the joints in the mooring system become relaxed. This allows sand particles into the spaces, which will then cause additional abrasion on these areas when tension is returned (Jootsen & Hoekstra, 2003). The elastic properties of the line ensure that the mooring line maintains a continuous tautness. This ensures that this additional abrasion cannot take place. Continual tautness also prevents contact with the seabed; this both prolongs the life of the mooring components by avoidance of abrasion, and protects the ecosystem around the anchor point from disruption by mooring lines (Irish, et al., 2005).

Another benefit compared to other compliant moorings is the reduction of excursion from the intended location of the mooring; this is due to a shorter pre-elongation length of mooring line can significantly reduce the swing circle of the mooring (IALA, 2005).

There are considerable variations in the method by which mooring components on the market achieve an elastic effect. The most simple approaches one or more natural rubber cords. The properties of natural rubber such as tear and abrasion resistance as well as its creep properties, high tear strength and excellent elongation properties make it a suitable candidate for mooring (Joosten, 2006).

Other rubber mooring cords use composition rubber including both natural rubber and synthetic rubbers designed to optimise performance. Replacement of steel chains and wire ropes with rubber components can reduce the weight of the mooring line by a factor of 10 (Joosten, 2006). This can reduce the overall loading on the mooring system, and reserve buoyancy.

The light weight compared to other mooring lines can also make handling during deployment much easier. Retrieval of the mooring system is potentially more complex as hauling the line aboard could damage the mooring line. Retrieval issues are resolved in several of the available mooring lines by running a length of synthetic "safety" rope long enough to allow the required range of elongation by the elastic cord, but prevent excessive over stretching in extreme conditions. This safety cord can also be used to haul the mooring on board the attending craft for maintenance.

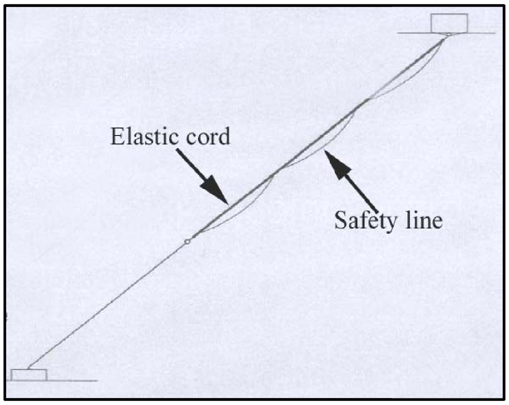


Figure 10 - Safety cord on elastic mooring line (IALA, 2010)

In the case of a tidal current generation, the energy generated must be transmitted to shore. This requires transmission cables to follow the line of the mooring lines. As explained in section 4.2, copper transmission wires have a very small elongation. One solution to this problem is being developed by Woods Hole Oceanographic Institute.

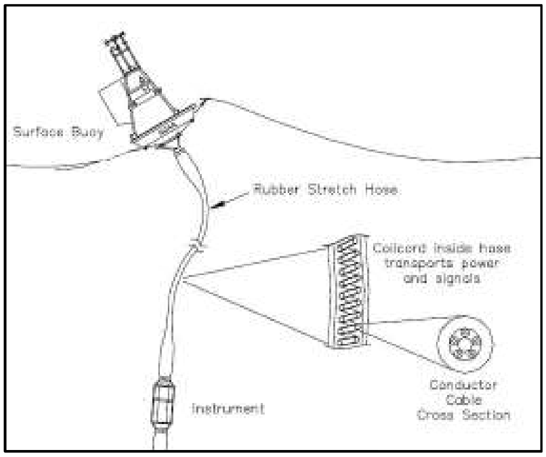


Figure 11 - WHOI coil cord elastic mooring design (Irish, et al., 2005)

Another issue which may arise from the use of elastic moorings are that they are more susceptible to cutting and breaking than their mooring line counterparts. This is mostly due to fishing equipment catching on the lines (Irish, et al., 2005). In the context of a tidal current generation farm it would be fair to assume that fishing vessels would not enter the farm area, although stray equipment could still be an issue.

There are a small number of companies who produce elastomeric tension members for moorings. They are currently used for pontoons, marinas and yacht moorings by companies including Seaflex, Supflex and Halzette, The Dutch lighthouse authority use Datawell rubber mooring tethers for their navigation buoys. Extensive research has also been undertaken by the Woods Hole Oceanographic Institute (WHOI) who are developing and testing elastomeric mooring tethers for their data collection buoys.

Datawell, who provide mooring components for the dutch lighthouse authority, have 40 years of experience in rubber moorings (Datawell, 2011). The maximum loading specification is for a load of 2tons is available at maximum lengths of 15meters.The natural rubber cord has a diameter of 50mm and has a shore hardness of 70. The maximum elongation of this specification is 300%. These mooring tendons have an option of a safety line. Quotations for the range of Datawell mooring tendons are listed in Appendix 1 (Scrivens, 2012).

Figure 12 -Termination of rubber mooring cord (Datawell, 2011)

The Hazelett mooring system is used for yacht and pontoon mooring. The mooring components can support loads of up to 35 tons. It is recommended that a regular elongation of 30% should not be exceeded to preserve the life of the system (Hazelett, 2010). If 30% normal elongation for normal loading and 100% elongation for extreme loadings are maintained then, the mooring

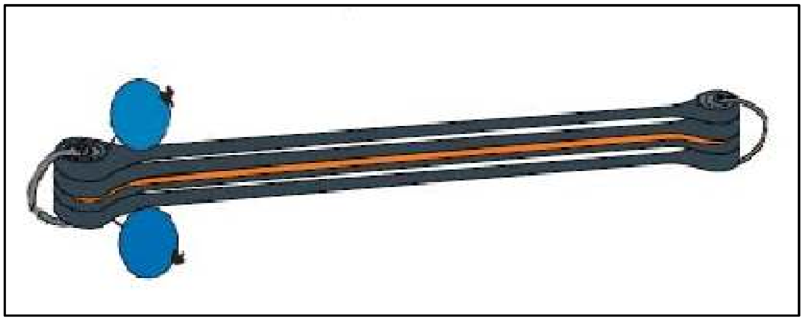


Figure 13 - Hazelett 35 ton mooring rode (Hazelett, 2010)

system should have a life of around 20 years (Oldport Marine Services inc., 2008). This module comes with an inbuilt safety line highlighted in orange in Figure 13. Communication from the supplier provided the cost for a 10ft. elastic line would cost \$880, at an exchange rate of \$1 = £0.62 this is £545.06 for 3.05 meters (Hill, 2012). 6 of these components are required to take a load of 50 tons.

Supflex mooring components, produced by American Marine, are primarily designed for the mooring of compliant pontoons and marinas. The technology uses composite rubbers to achieve a high load capacity. The range in load capacity is generated by variations in rubber cord diameter and the number of cords per mooring component up to 600 strands; a maximum break load of 1900tons. These components have the option for a safety line which is contained in the centre of the rubber mooring cords.

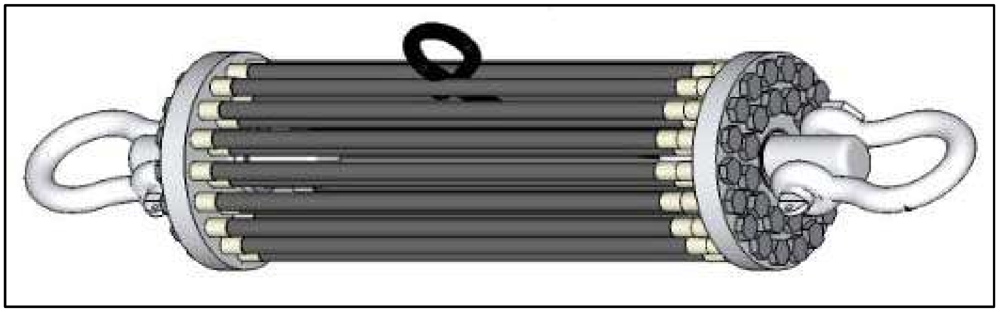


Figure 14 - Supflex 30 strand elastic mooring component

Out of the elastic mooring tendons on the market, this is the only one which is currently designed to support a big enough load for a tidal current turbine, however Supflex did not respond to requests for information on costs and performance of this device.

The Seaflex elastic mooring components claim to be able to reducing the lifetime cost of the system by increasing maintenance intervals and the life of the mooring line (Bengtsson & Ekström, 2012). The life of this component is expected to be 10 years and is designed to support a load of 10kN. Seaflex did not respond to requests for further information.

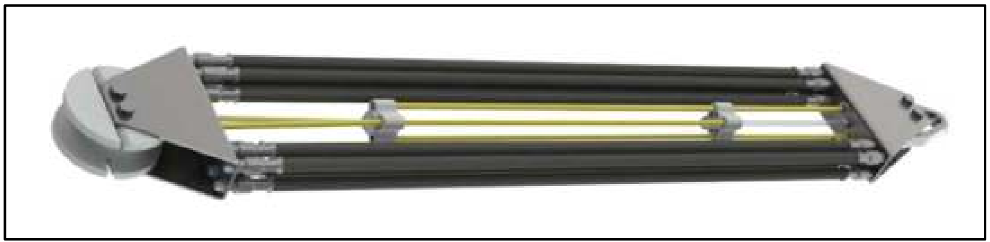


Figure 15 - SEAFLEX® with 8 rubber hawsers (Bengtsson & Ekström, 2012)

Potential benefits of elastomeric mooring lines compared to other line types include lighter weight than steel chain or wire rope. The life expectancy varies from company to company but is estimated to be between 10 and 20 years, which could significantly reduce the cost of maintenance. The compliance it provides could also reduce maintenance of the device itself since shock loads are prevented by the use of these lines.

The extensive experience the use of chain in mooring lines gives this option a lot of credit. Life expectancies and costs can be predicted quite accurately. Synthetic fibre ropes are lightweight but the lifetime of this sort of line in a marine environment is not long.

Wire rope can provide significantly longer life expectancy than other line types, however it is subject to kinking, which reduces the performance of the component significantly, particularly at joints. It therefore requires careful transport, deployment and retrieval to avoid this.

Eventually the selection of mooring line type will depend on the design life of the mooring, environmental conditions and the loading requirements of the device. Elastomeric mooring tendons certainly have the potential to provide several benefits and are an option well worth investigation for its use as mooring line for tidal current turbines.

9 Elastomeric mooring tendons

Consider a subsurface horizontal axis tidal current turbine on a single taut mooring line. The turbine is neutrally buoyant so that in slack tide, the device self maintains a constant height. The position of this turbine will depend on the overall buoyancy of the system and the drag forces which will vary depending on the velocity of the passing current.

9.1 Assumptions

The following assumptions are made for the performance of the turbine:

- Turbine is neutrally buoyant and self stabilising.
- Rotor diameter = 10m
- Turbine coefficient of power = 0.4
- Cut-in speed = 1m/s
- Rated speed = 2.5m/s
- Rated power = 250kW

The assumptions of the performance are considered reasonable estimates for a tidal current turbine, and the coefficient of performance is comparable with scale testing of the Nauticity tidal current turbine; CoRMaT (Clarke, et al., 2008).

Assumptions on the environmental conditions for the location of the turbine are:

- Maximum current velocity at spring tide = 3.5 m/s
- Maximum current velocity at neap tide = 1.7 m/s
- Tidal cycle duration = 12 hours 24 minutes
- Spring-neap-spring cycle = 14 days
- Total water depth = 100 meters
- Density of sea water = 1020 kg/m^3

These assumptions are based on the current velocities at the EMEC test site; the Fall of Warness in Orkney, Scotland. The tidal cycle is based on a typical tidal cycle as described by the National Oceanographic and Atmospheric Administration (NOAA, 2004).

9.2 Current velocity

The current velocities given for spring and neap tides are representative of the velocity on the surface of the body of water. In practice, the velocity decreases with depth. This is due to the effects of the boundary layer on the seabed where the velocity is ≅ 0m/s. The velocity profile follows the 1/7th power law (Frankel, 2002). This law considers the transition between boundary zero velocities and minor pressure gradients with occur with depth (De Chant, 2005).

The velocity for any given depth (v_h) can be calculated using the equation:

$$\boldsymbol{v_h = v \times \left(\frac{h}{z}\right)^{\frac{1}{7}}}$$

Where $\boldsymbol{v}$ is the velocity on the surface of the water, $\boldsymbol{h}$ is the height above seabed and $\boldsymbol{z}$ is the total depth of the water. The velocity profile for a total depth of 100meters is represented in Figure 16.

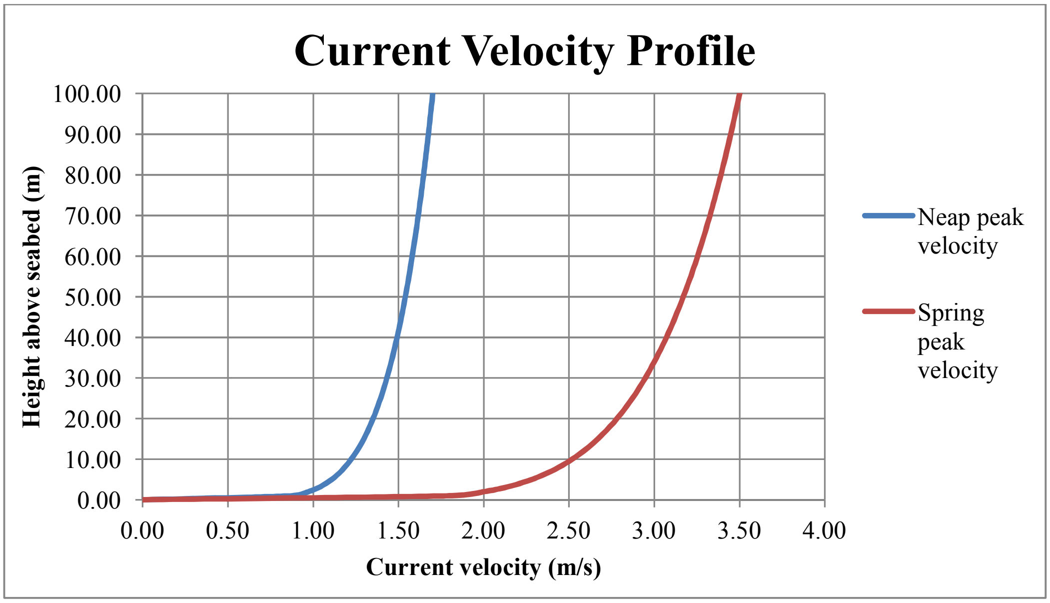


Figure 16 - Velocity profile for 100 meters depth using 1/7th power rule

Obviously higher velocities are closer to the surface of the water. In fact 75% of the power available is in the upper 50% of the stream (UK Department of Energy, 1990). To maximise the output of the tidal current turbine it would seem advantageous to maintain as much height as possible.

In addition to maximising the output of the device, avoiding collision with the seabed is vital. The drag forces which act on the turbine will be inclined to push the turbine towards the seabed. The turbine is essentially follows a curve equivalent to an arc with the radius equal to the length of the mooring line centred around the point of anchorage.

In order to maintain a reasonable height for the turbine, a buoyant force, or lift force should be incorporated into the system.

9.3 Force calculations

Two options will be investigated in the following scenarios. The first option will use a spherical buoy to provide a buoyant force. The second option will use a hydrofoil with small reserve buoyancy. Both options will be positioned on an additional line connected on an additional line above the turbine. The drag forces on the turbine will also be considered in the force calculations.

9.3.1 Turbine

The turbine forces will be consistent throughout these calculations, an will follow the assumptions stated in section 9.1.

The drag (horizontal) force on the turbine ($\boldsymbol{F_{DT}}$) is given by:

$$\boldsymbol{F_{DT}} = \boldsymbol{C_{DT}} \times \mathbf{0.5} \times \boldsymbol{\rho_w} \times \boldsymbol{A_T} \times (\boldsymbol{v_h})^{\mathbf{2}}$$

Where $\boldsymbol{C_{DT}}$ is the coefficient of drag on the turbine, $\boldsymbol{\rho_w}$ represents the density of sea water and $\boldsymbol{A_T}$ is the swept area of the turbine.

The angle of the mooring line from the seabed (θ) can be found using:

$$\boldsymbol{\theta} = \tan^{-1}\left(\frac{\boldsymbol{Drag\ forces}}{\boldsymbol{Buoyancy\ and\ lift\ forces}}\right)$$

Obviously the buoyancy and lift forces are required to calculate θ. This also allows the turbine height above the seabed to be calculated using further basic trigonometry.

9.3.2 Spherical buoy

The buoyancy force generated by the spherical buoy is defined as:

$$\boldsymbol{B} = \left(\rho_{w-}\rho_a\right) \times \boldsymbol{V_b} \times \boldsymbol{g}$$

Where $\boldsymbol{B}$ is the buoyant force of the buoy, ρ_a is the density of air, $\boldsymbol{V_b}$ is the volume of the buoy and $\boldsymbol{g}$ is the gravitational force.

To assess the appropriate buoyant force required, the drag forces acting on the device must also be considered. This will include both the drag forces on the turbine and the buoy. The drag force on the spherical buoy ($\boldsymbol{F_{DB}}$) is calculated using the equation:

$$\boldsymbol{F_{DB}} = \boldsymbol{C_{DB}} \times \boldsymbol{0.5} \times \rho_w \times \boldsymbol{A_B} \times (v_h)^{\boldsymbol{2}}$$

Where $\mathbf{F_{DB}}$ is the drag force on the buoy, $\boldsymbol{C_{DB}}$ is the coefficient of drag on the buoy $\boldsymbol{A_B}$ is the characteristic area which in this case is the cross sectional area of the buoy normal to the direction of current flow.

Typical mooring configurations use chain or wire ropes, which have a minimal elongation under load. The turbine described, moored on a non- elastic mooring line is now considered. The turbine heights for a range of buoy diameters, for a turbine moored using a non-elastic mooring line are shown in Figure 17.

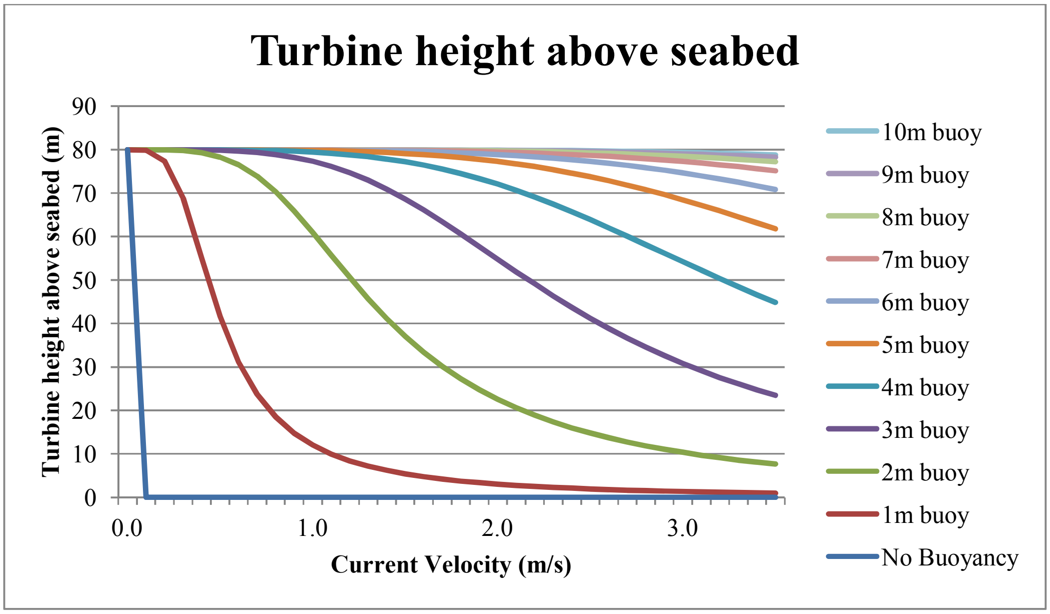


Figure 17 - Height of tidal current turbine with increasing additional buoyancy.

The graph in Figure 17 represents, undeniably, the requirement for an additional buoyancy force to maintain a reasonable height for the turbine above the seabed. Without any buoyancy the turbine is immediately forced to the seabed with even a slight current. This is obviously not desirable since the turbine would not be able to function and would cause serious damage to the device. The smaller buoyancy forces do not maintain a sufficient turbine height to ensure that the contact is not made with the seabed.

Assuming that the majority or power to be generated is in the upper 50 percent of the tidal stream, the turbine height should be maintained above 50 meters. To do this the minimum required buoyancy should be provided by a spherical buoy of 5 meters diameter. A 6 meter diameter buoy would provide an additional benefit in the higher velocity currents.

In the case of the larger buoys, from 7 to 10 meters diameter, it can be seen that the additional buoyancy does ensure that of a height close to the maximum is maintained, even at height current velocities. The drag on these larger buoys means that the full height of the turbine cannot be maintained.

There are also other implications of specifying buoys of these sizes. The buoyant force on the line and anchorage must be considered. The buoyant force provided by the 5 meter diameter buoy is calculated as 650kN, the buoyant force of the 6 meter diameter buoy is 1130kN, almost 2 times the force.

Whilst this is beneficial for maintaining the height of the turbine, the vertical loading on the anchorage and the mooring line are significantly increased. When considered that the drag force on the turbine at a peak velocity of 3.5m/s is 420kN, only one third of the vertical force from the buoy. The implications of this are; that the cost of the mooring equipment will certainly be higher since it will have to be specified to sustain a significantly higher load.

In addition, the large buoy will mean that the turbine will have to be sited originally lower down in the water, in order to be below the surface of the water and to avoid turbulence caused by wave action. This will reduce the benefit of maintaining a consistent height, as the current velocity will be reduced with depth.

Logistically, transport of buoys these sizes will be more complex. In addition, buoys of this size are likely to be a lot more expensive and not so readily available in the marketplace.

Considering the reasons stated previously, a 5 meter diameter turbine would seem the most appropriate size for the system. The logistics of transportation, its position in relation to the turbine, buoyancy force loading on the mooring line and height keeping of the turbine indicate the 5 meter diameter buoy as the preference.

9.3.3 Hydrofoil

Another option for supplying lift to the mooring system is to use a hydrofoil instead of a simple buoy. The hydrofoil has a small amount of buoyancy to support it during times of slack tide, and generates lift as the current begins to flow.

For the case where the buoyant and lift forces are provided by a hydrofoil, a symmetrical hydrofoil will be used for simplification of the calculations. The National Advisory Committee for Aeronautics (NACA) standard 0012 foil profile is used here. The 12 in the profile title describes the relation of the maximum thickness of the foil to the cord length; the maximum thickness is 12% of the cord length. This is a symmetrical foil shape. The angle of attack (α) is the angle between the direction of current flow and the chord line of the hydrofoil.

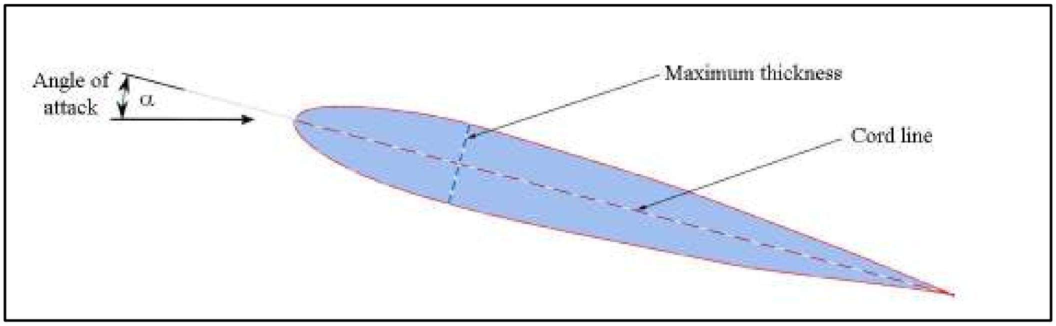


Figure 18 - NACA 0012 cross sectional dimensions

The coefficients of drag and lift for the hydrofoil are described in tables which are the result of experimental and simulation data (Sheldahl & Klimas, 1981). The results provide coefficients as a function of the Reynolds number and the angle of attack of the flow relative to the position of the foil.

The Reynolds number ($\boldsymbol{Re}$) is calculated using the following equation:

$$\boldsymbol{Re} = \frac{\boldsymbol{\rho * v * L}}{\boldsymbol{\mu}}$$

Where $\boldsymbol{L}$ is the characteristic dimension, in this case, the cord length and $\boldsymbol{\mu}$ is the dynamic viscosity of the fluid, for sea water at 10°C is 0.0135 kg/m.s.

Knowing the Reynolds number for the characterised flow, the lift and drag coefficients for the hydrofoil can then be taken from tables. The tables used for this case can be found in Appendix 2.

The calculation of drag on the hydrofoil is the same as for the drag on the buoy, however this time the coefficient of drag varies with current velocity. The lift generated is calculated by the equation:

$$\boldsymbol{F_{LH} = C_{LH} \times 0.5 \times \rho_w \times A_H \times (v_h)^{2}}$$

Given $\boldsymbol{y_1}$, the length of the mooring line, the turbine height can now be calculated by:

$$\boldsymbol{h = y_1 \times \sin\theta}$$

The resulting lift forces for a NACA 0012 foil with a chord length of 8 meters and a width of 12 meters were calculated. In an array situation the footprint of the system is to be kept to a minimum. The width of 12 meters is therefore logical; as the width of the turbine swept area is also 10 meters and having a hydrofoil of much greater width would have significant implications on the footprint of the system. A hydrofoil of a width in large excess of this does provide more lift however is unlikely to be suitable in a tidal current turbine array. This hydrofoil size also allows a comparison with the 6 meter diameter buoy system.

The calculations carried out give the elevation of the turbine as shown in Figure 19.

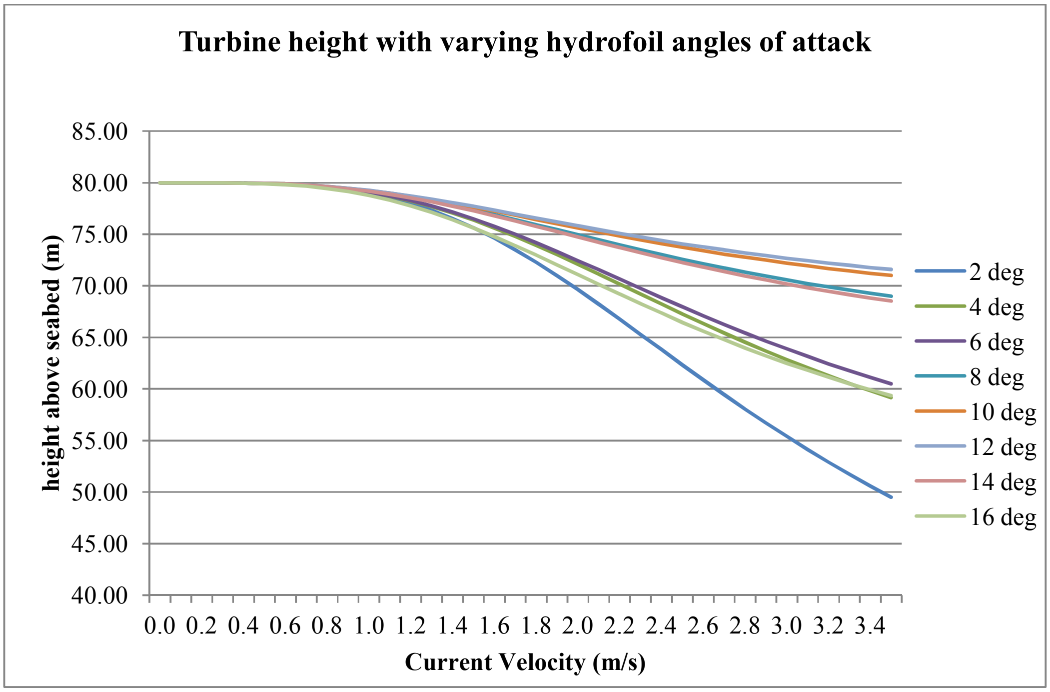


Figure 19 - Turbine height with varying hydrofoil angles of attack for a NACA 0012 shape

From Figure19 it is clear that the optimum angle of attack (α) is 12 degrees, although an angle of 10 degrees would produce similar results of maintenance of maximum turbine height. It would be possible to increase the lift and buoyancy forces provided by the hydrofoil, however, if the foil becomes larger than the turbine itself then logistical issues are likely, so for the purposes of these calculations are not considered.

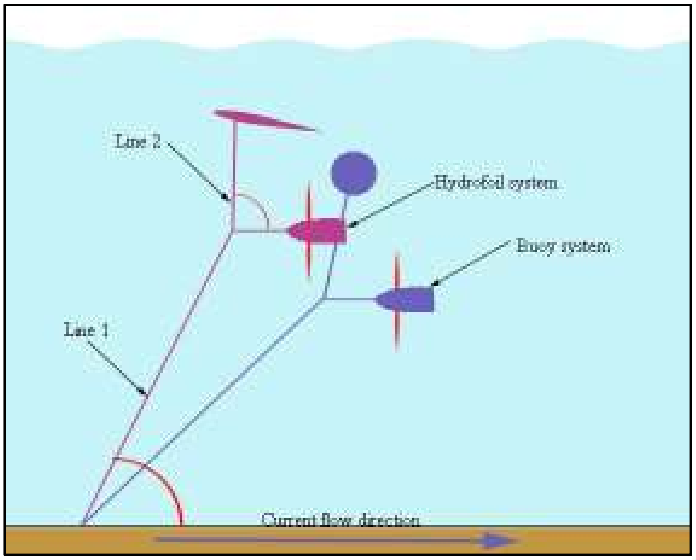


Figure 20 - Comparison of the position of turbine with hydrofoil and buoy systems at 3.5m/s current velocity

9.4 Elastic mooring lines

All of the above calculations assume that the mooring line used is inelastic and that the line length will remain constant. The drag forces on the system mean that the turbine will be susceptible to variations in height, and therefore productivity.

Now consider an elastic mooring line. If the turbine is to remain at a constant height; the mooring line will be required to elongate. The elasticity of the mooring line could be provided by a section or the full length of the line. It is reasonable to assume that the elongation could be provided by a section of the mooring line rather than the whole line, however, a range of component lengths are explored for the spherical buoy and hydrofoil systems. The elasticity will most likely be provided by rubber cords as described in section 8.4.4.

9.4.1 Elastic mooring line – Spherical Buoy

Despite the additional buoyancy provided in the system by the buoy, a consistent height for the turbine cannot be maintained without considering an elastic mooring line. The resulting horizontal displacements for the range of tidal current velocities were calculated. The required extensions of the mooring line, for a system using a 5 meter diameter buoy, provided by a range of elastic component lengths were calculated using trigonometry and are shown in Figure 21.

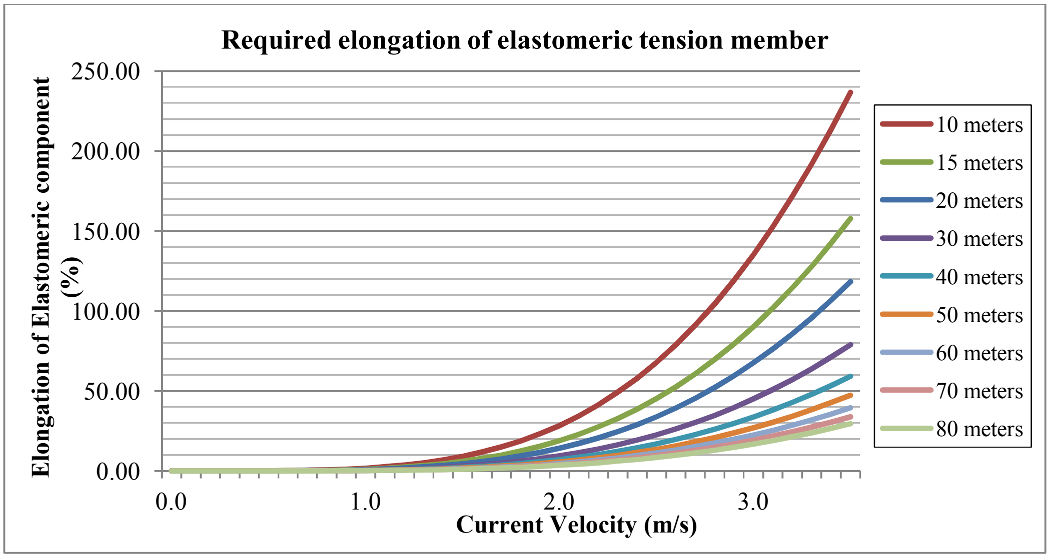


Figure 21 - Required elongation of elastomeric tension member – Variable tendon length 5 meter buoy diameter

This graph shows the optimal elongation of the elastomeric tension member required to maintain a constant turbine height of 80 meters in a water depth of 100 meters. The percentage of required extension depends greatly on the length of the elastomeric tension member. It is clear from the Figure 21 that the elongation required escalates rapidly at velocities above 2m/s from elongations of less than 30 percent up to almost 230 percent for the shortest elastic components.

The 80 meter component requires an elongation of only 30 percent at a current velocity of 3m/s. This is outside of the elongations achievable from traditional mooring lines, including synthetic ropes. To achieve these proportions of elongation; it will be necessary to use elastic moorings.

The same calculations were carried out for a system using a 6m diameter buoy and the results for required elongation are shown in Figure 22.

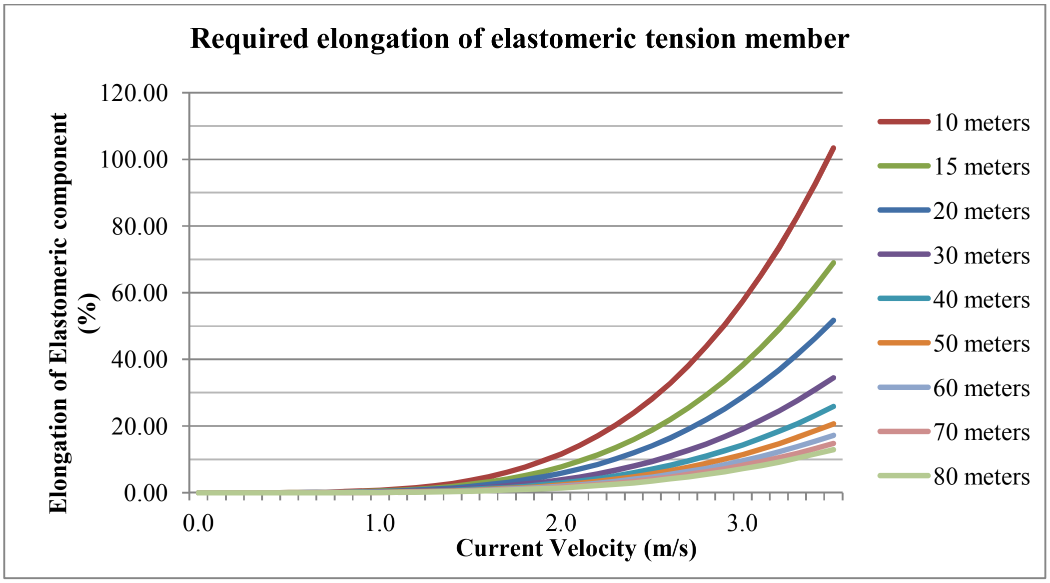


Figure 22 - Required elongation of elastomeric tension member – Variable tendon length 6 meter buoy diameter.

These results show a significant difference for a relatively small increase in buoy diameter. The maximum elongation required for a 10 meter elastic tendon is 104 percent. For the full mooring length of 80 meters the elongation required is as small as 13 percent.

9.4.2 Elastic mooring line – Hydrofoil

The behaviour of the system with the hydrofoil is quite different from that of the buoy. The same calculations were done for the hydrofoil system with a range of elastic component lengths. The results are shown in Figure 23.

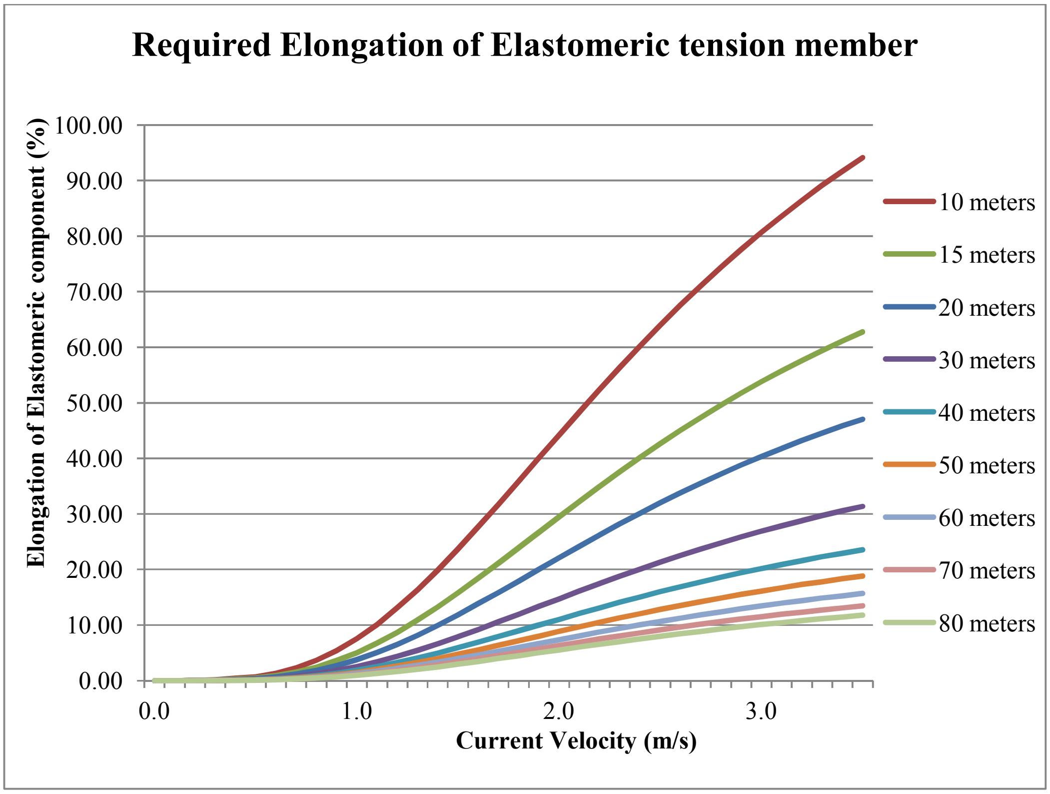


Figure 23 - Required elongation of elastomeric tension member – Variable tendon length hydrofoil

It is clear that the elongation requirements of the hydrofoil vary greatly from the buoy system. The initial requirement of the 10 meter elastic component is only 94 percent. Above elastic component lengths of 40 meters the elongation required is less than 20 percent and as small as 12% for the full length elastic mooring line. For the longer components the elongation is not significantly smaller than that of the buoy system.

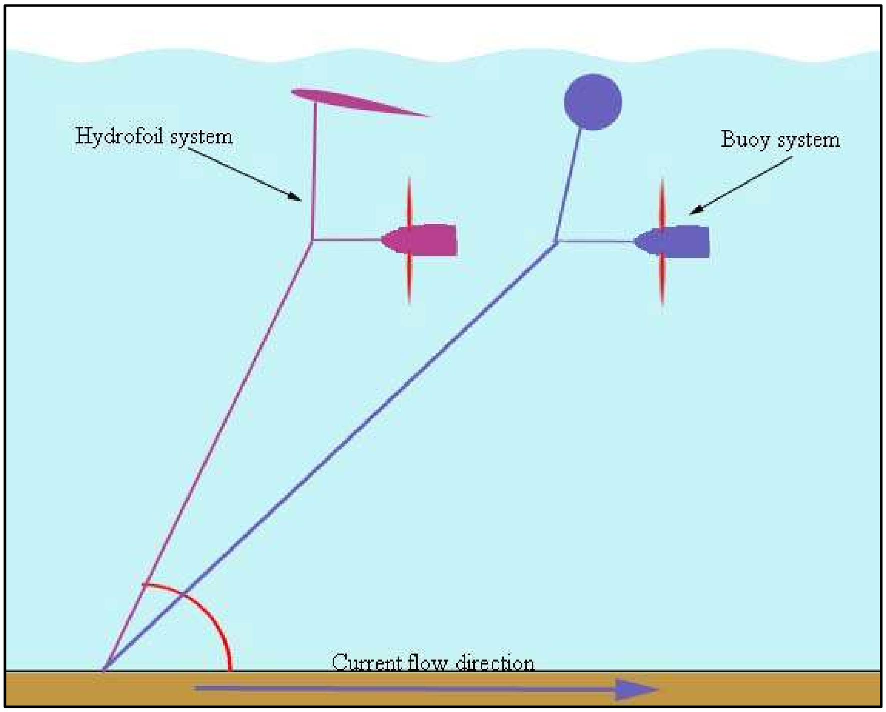


Figure 24 - Comparison of the position of turbine with hydrofoil and buoy systems on elastic moorings at 3.5m/s current velocity

A comparison of each system is shown in Figure 25 for component lengths of 10 meters, 40 meters and 80 meters.

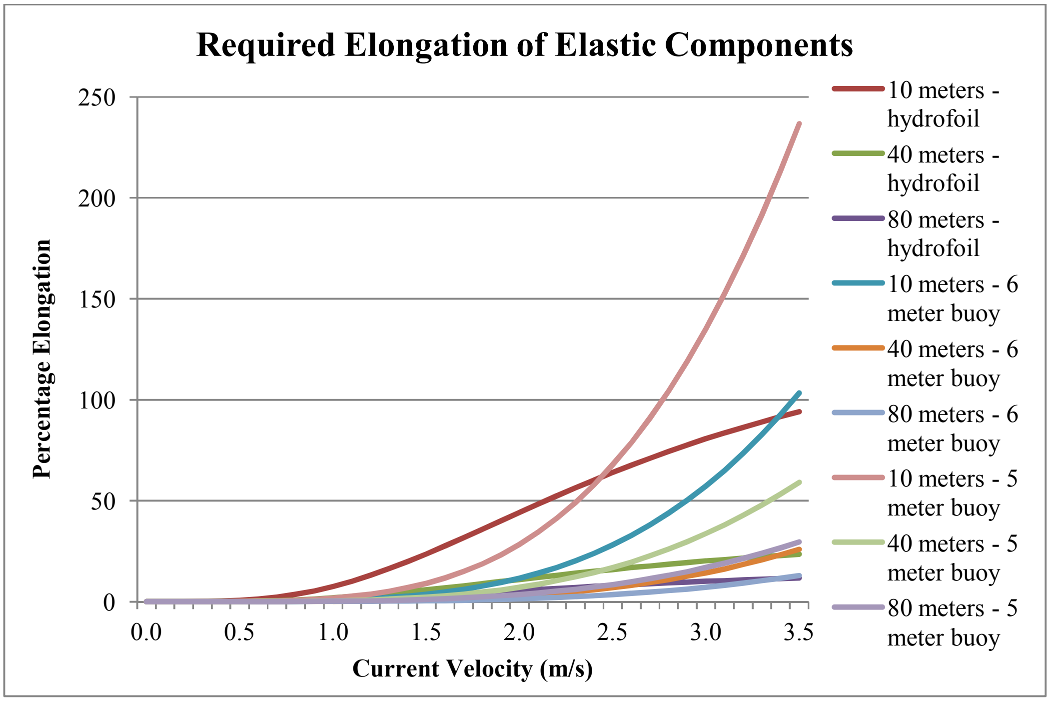


Figure 25 - Required elongation of elastic components - system comparison

From this graph it is clear that the 5 meter buoy requires significantly greater elongation. The 6 meter buoy and the hydrofoil are comparable with only a few percent variations in elongation requirements. Comparisons of the shapes of the elongation curves give different behavioural results. These shapes will have implications on the compatibility with the performance of the elastic member.

The systems investigated in this section were; a system using a 5 meter diameter buoy, a system using a 6 meter diameter buoy, and a system using a hydrofoil. Each of these options was investigated for the resultant turbine height given a non-elastic mooring line for a range of current velocities. Each system was then considered with elastomeric mooring tendons. The required elongation of these tendons for a range of elastic component lengths was calculated. The results of this investigation show that depending on the length of the tendon, the required elongation varies greatly.

The minimum elongation required (12 percent) was given by the hydrofoil system with the elastomeric mooring tendon occupying its full length. The data calculated should provide a basis for establishing the feasibility of using elastomeric mooring tendons, both functionally and economically. The best option will depend greatly on the behaviour of available mooring tendons, and the cost benefit of each system.

9.5 Power Output

To assess the benefits of each system, the power output must be considered. The power output will dictate the return on investment which is the key criteria for deployment of tidal current turbines. The systems must be compared and the best economic outcome selected.

The power output from the turbine between the cut-in speed and the rated speed is governed by the equation:

$$\boldsymbol{P = C_{PT} \times 0.5 \times \rho_w \times A_T \times (v_h)^3}$$

Where $\boldsymbol{C_{PT}}$ is the coefficient of performance of the turbine.

The instantaneous power output from the turbine above the rated speed is given by:

$$\boldsymbol{P = C_{PT} \times 0.5 \times \rho_w \times A_T \times (v_r)^3}$$

Where $\boldsymbol{v_r}$ is the rated speed of the turbine. This equation assumes that there is no cut-out speed for the turbine.

This comparison only considers the 5 meter buoy since the requirements of the mooring line and anchorage for the 6 meter buoy are considered excessive, despite the benefits of the additional buoyancy.

The hydrofoil system with the inelastic line has been calculated to give a total energy output over one tidal cycle of 14 days of 30.32MWh, and an annual output of 788.42MWh.

The 5 meter diameter buoy system with the inelastic line has been calculated to give a total energy output over one tidal cycle of 14 days of 30.48MWh, and an annual output of 792.53MWh.

The total energy output of both the buoy and the hydrofoil systems, with an elastic mooring line allowing a constant height to be maintained, can generate 30.77MWh per cycle and 800MWh per year.

Table 5 - Output of tidal current turbine systems

System	Per cycle (14 days)	Per year
Hydrofoil - inelastic	30.32MWh	788.42MWh
5 meter buoy - inelastic	30.64MWh	792.53MWh
Elastic line	30.77MWh	800MWh

The elastic mooring line allows the hydrofoil system to generate 11.52MWh more than the same system with an inelastic mooring line. An elastic line also allows the buoy system with to generate 7.47MWh more than with an inelastic mooring line.

The graphs showing the power outputs for each system over a full tidal cycle of 14 days can be found in Appendix 3.

A close up of the power output over a diurnal tidal cycle is showing in Figure 26.

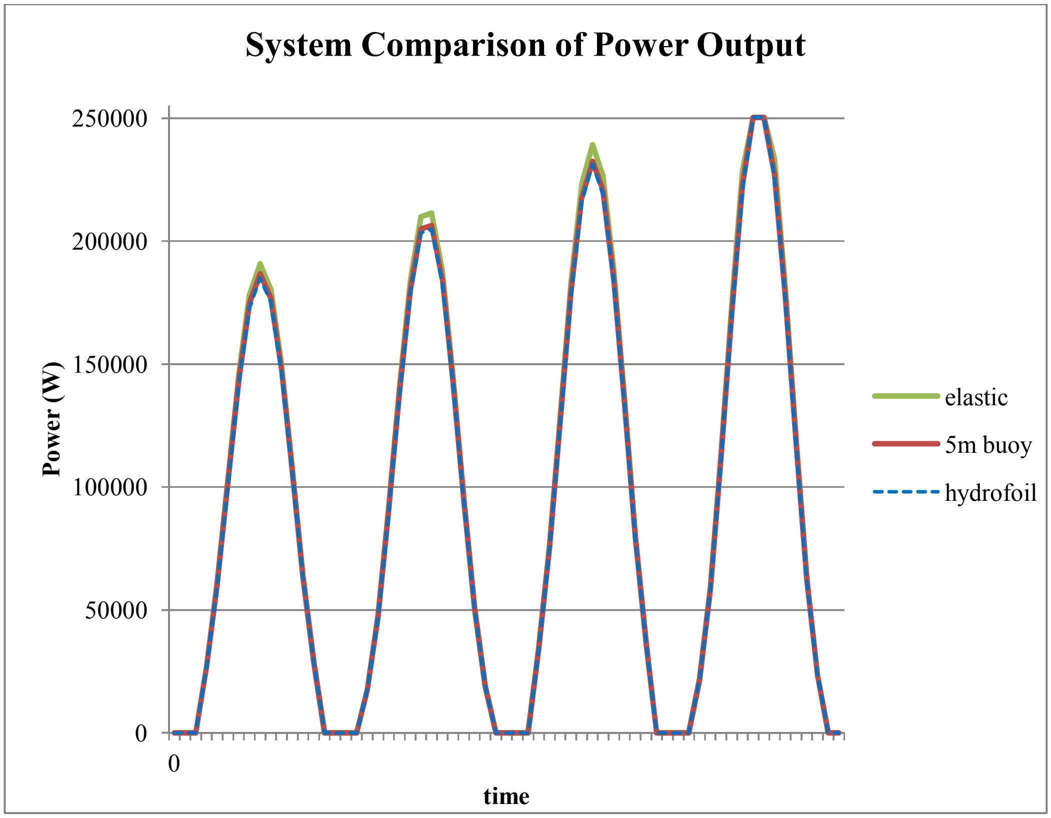


Figure 26 - Power generation comparison between elastic and inelastic mooring line for buoy and hydrofoil systems

This graph shows the difference in power generated amongst the systems over one diurnal cycle as the output approaches rated power. The difference mostly occurs at the peaks of output, when the drag force is greatest. It can be seen that there is an improvement in the power output of the system with an elastic mooring line. This improvement is even more significant for the hydrofoil system.

If an assumption of a turbine life of 25 years is made, then the difference in energy generation over the lifetime between the hydrofoil system with a non elastic mooring line and an elastic mooring line is 288MWh

For the assumption of a 25 year turbine life, the increase in output due to the elastic mooring line on the 5 meter diameter buoy system is 186.75MWh.

9.6 Behaviour or elastomeric tension members

Now that the elongation requirements of the mooring line are known, they can be compared with the actual performance of elastic mooring lines.

The primary function of the elastic mooring in this system is to maintain a constant height for the turbine. To achieve this, the behaviour of the mooring component must be closely comparable to the elongation requirements described in the previous section.

The actual performance of the rubber mooring line depends on the composition of the rubber and the processing of it. For comparison with the requirements of the elastic mooring line, the load- elongation curves of rubber can be studied. A generic example of the load - elongation curve of a rubber mooring tendon is shown in Figure 27.

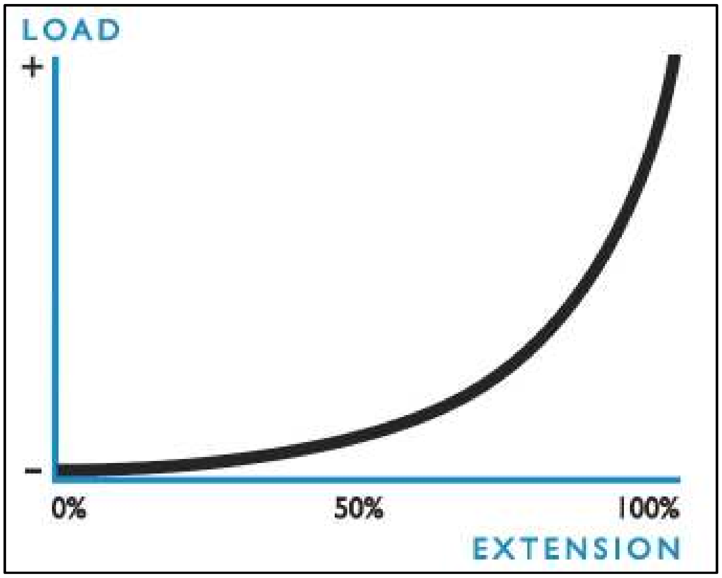


Figure 27 - The progressive load curve of SEAFLEX® hawser. (Bengtsson & Ekström, 2012)

For the function of the elastomeric mooring tendon to maintain the height of the turbine at a constant height, the load – elongation curve must match.

The load – elongation curves of the buoy system and the hydrofoil system are shown in Figures 28 and 29 respectively.

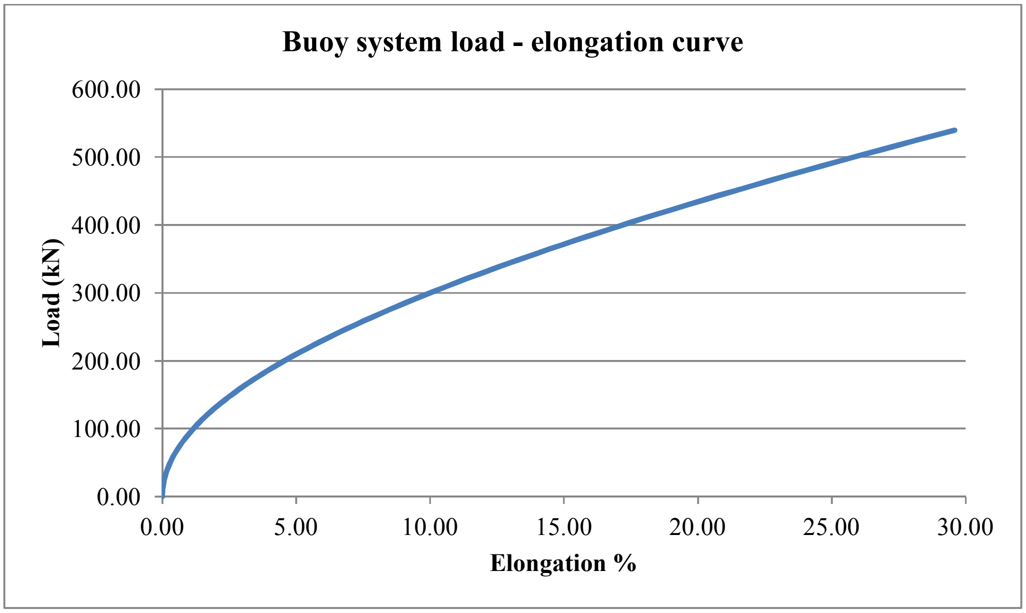


Figure 28 - Buoy system load - elongation curve

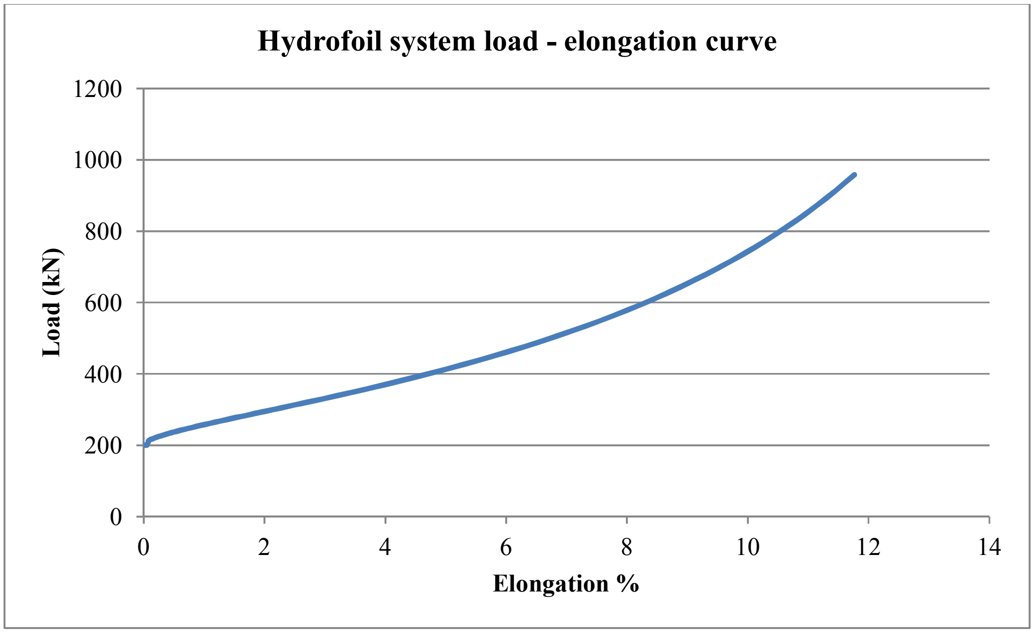


Figure 29 - Hydrofoil system load - elongation curve

It can be seen from these graphs quite clearly that the hydrofoil system has a better match with the generic load – elongation curve for the relevant elongation percentage. This comparison is not definitive and further investigation and testing of a range of rubber compositions to establish the appropriateness of the elastic mooring line to the system. It is also possible that elastomeric mooring tendons could be produced to match the requirements of the buoy system.

10 Economics of flexible moorings

There is a great deal of uncertainty when it comes to putting a price on tidal current energy. Many of the speculative costs which are out there are estimates from experience in other industries. With time and experience, the price will become clearer. There are several costs for a tidal current turbine described in Figure 30.

Flowchart representing costs of a tidal current turbine mooring throughout its life.

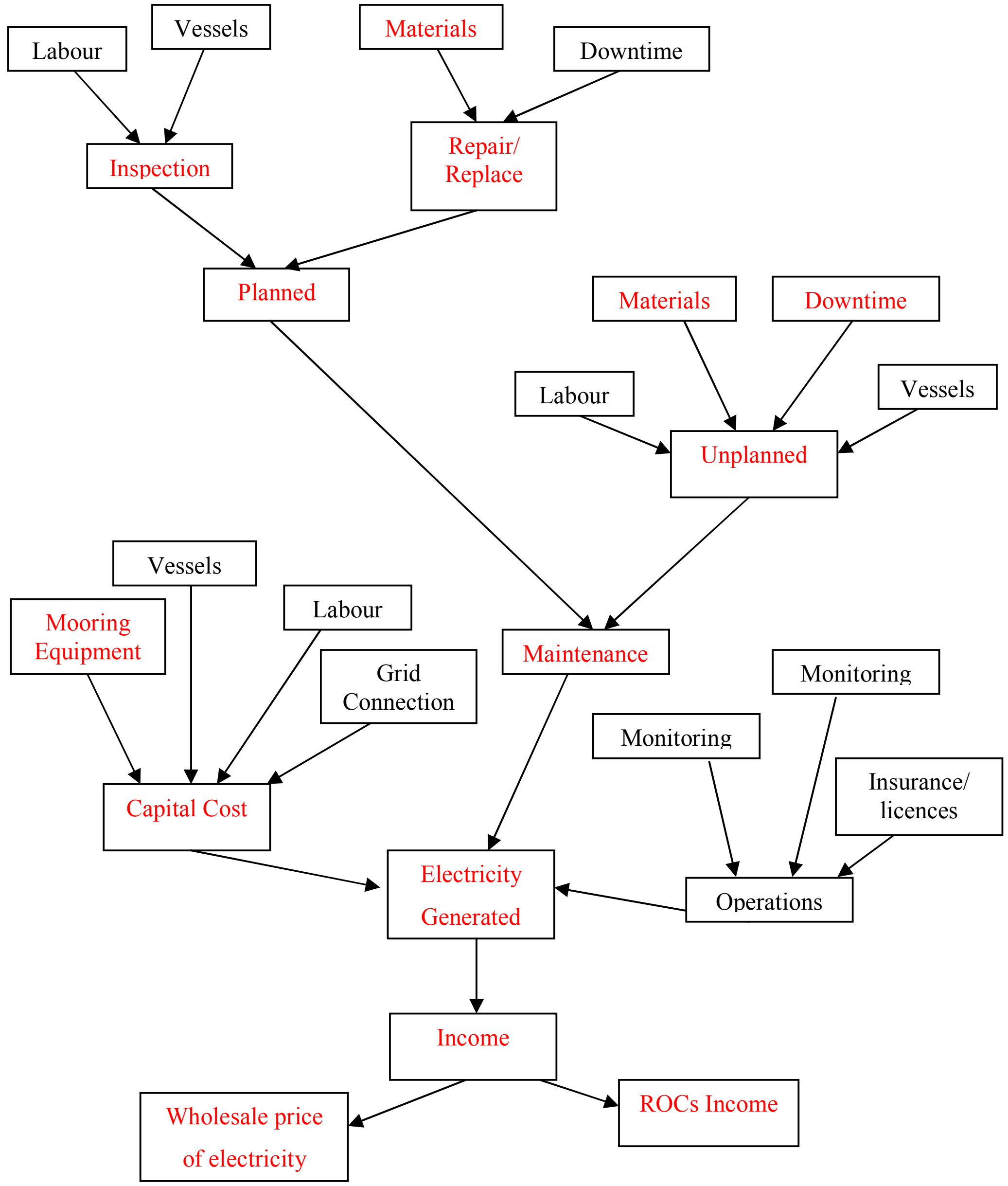


Figure 30 - Lifetime costs of turbine mooring

This study will investigate the cost comparison of a tidal current turbine supported by a 5 meter diameter spherical buoy with a non elastic mooring line and an elastic mooring line.

From the calculations in the previous section, the theoretical power output of the 250kW tidal current turbine at a constant height, enabled by the elastic mooring, is 800MWh. The equivalent power output from the same turbine on a non-elastic mooring is 792.53MWh. This is an output difference of 7.47MWh per year.

Assumptions made for this section are as follows:

- The wholesale price of electricity during 2012 so far has been between4.46 – 5.29p/kWh (Bluemark Consultants, 2012). The cautious assumption that the wholesale market price of electricity is 4.5p/kWh or £45/MWh can be applied, although this price is highly liable to change throughout the life of the system.
- 3 ROCs will be awarded for tidal energy in Scotland at £40.71/MWh (DECC, 2012) (correct at time of writing). This is also liable to change, or even removal during the life of the system.
- The design life of the system is 25 years. This is in line with targets from developers.
- The cost of 100 meters of steel chain costs £2500 (Owen, 2012).
- The life time of steel chain mooring is taken to be 5 years (Owen, 2012).
- The nominal cost of a mooring inspection is £1500 (Robinson, 2012).
- If the remainder of the systems are identical then a cost comparison can be carried out.

Table 6 shows a breakdown of the mooring costs associated with the mooring of a tidal current turbine. The data which is filled in the table are estimates of likely costs. The omitted data is even more unknown and has been omitted for this reason.

Table 6 – Mooring cost comparison - elastic versus non-elastic mooring line

	Non-elastic mooring line		Elastic mooring line	
	Cost (£)	Number of times	Cost (£)	Number of times
Capital cost	2500	1	?	1
Replacement	2500	4	?	1
Inspection (labour, vessels, downtime)	1500	?	1500	?
Emergency (labour, vessels, downtime)	?	?	?	?
Subtotal	?		?	
Electricity wholesale	£ 45	792.53	£ 45	800
ROC income	£ 122.13	792.53	£ 122.13	800
Subtotal	£ 132455		£ 133704	
Life Subtotal (25 years)	£ 3 311 375		£ 3 342 600	
Total balance	?		?	

The difference in income between the two mooring lines over the 25 year life is £31225.

There several unknowns in the costing of both systems. Maintenance frequencies are one of the particularly uncertain areas, particularly in the case of emergency maintenance, by its emergency nature, is difficult to predict the frequency of this occurrence.

It is difficult to assess the full costs of the system over its lifetime. Assuming like for like, in all respects other than the mooring system, the cost of the elastic mooring system and replacements should be offset by reductions in inspection and maintenance requirements and the increased income enabled by the behaviour of the elastic mooring. This is assuming the difference in capital cost between the elastic and non-elastic mooring lines is less than the financial benefit of the elastic mooring line - (£31225 + £saved from less frequent inspection).

11 Conclusions and Recommendations

With the need for new and sustainable sources of energy to ensure security and diversity of supply in the UK and worldwide, it is vital such a predictable and immense resource, as tidal currents is utilised. The UK, one of the most naturally endowed countries, is at the forefront in this technology. Government targets are promoting and providing incentives for the development of technology to generate power from this resource. However, if tidal current generation is to become economically competitive with traditional types of generation, the industry must focus on reducing the cost of energy to at most 20 percent of its current cost. To do this, the two main cost centres which must be targeted are installation and maintenance.

One method which could reduce both of these costs is to use flexible moorings for tidal current turbines. The use of flexible moorings instead of pile structure foundations can significantly reduce the cost and time involved in installation, reduce the structural costs of the device and its mounting, utilise natural optimization of orientation of the device to current flow without the use of any control systems, reduce maintenance costs by allowing removal of device for onshore maintenance and also reduce downtimes.

It is unclear as of yet how much the savings are likely to be from using flexible moorings instead of piled structure foundations, however the opinion of industry bodies and developers is that the reductions in cost are likely to be substantial.

Since there is minimal experience with moorings for tidal current turbines; the experience, guidelines and regulations of other marine industries must be drawn upon until the tidal current energy industry builds experience of its own. Several of the respected marine industry regulators have begun to develop guidelines for the marine energy industry, for their own experience. By nature this guidance focuses more on general principles rather than case specific guidelines. The implication of this is that each case should be designed individually, taking into consideration the device and its surroundings.

The options for mooring anchors, lines and constructions were investigated with several options requiring specific tailoring to the device, its location and environmental conditions. These options include the use of elastic mooring tendons for the mooring of tidal current turbines. This option was investigated in further detail. Experience with this type of mooring line comes mostly from yacht, pontoon and marina mooring as well as mooring of navigation and oceanographic data buoys. Furthermore, elastic mooring technology has begun to be developed as an option for mooring marine energy converters. The properties of elastic mooring lines lend themselves to use in marine energy converters, namely for their ability to provide compliance for protection against rough seas, as well as their light weight and long life expectancy compared to its chain counterpart.

Additionally the elastic mooring line has the potential to improve the performance of a tidal current turbine. This improvement requires elongation of the mooring line to allow the turbine to remain at a constant height and therefore remain in the maximum current velocity in any given channel.

It remains to be seen whether or not the behaviour of elastic mooring lines can be matched with the requirements for elongation to optimise the power output of a tidal current turbine. In the event that the elastic mooring lines can provide the appropriate behaviour, the cost of the mooring line could be offset, and more, by the improvement in power output.

It is difficult to predict exactly how great the benefit would be, if any, since the wholesale price of energy and subsidies which exist at present are likely to change in the near future. Furthermore, the maintenance requirements and life expectancy of this technology are unknown as they there is not any experience using it for the application of marine energy conversion. Further research and testing with elastic moorings for marine energy conversion will be required to determine if this option really is of benefit. It is certainly an option worth pursuing.

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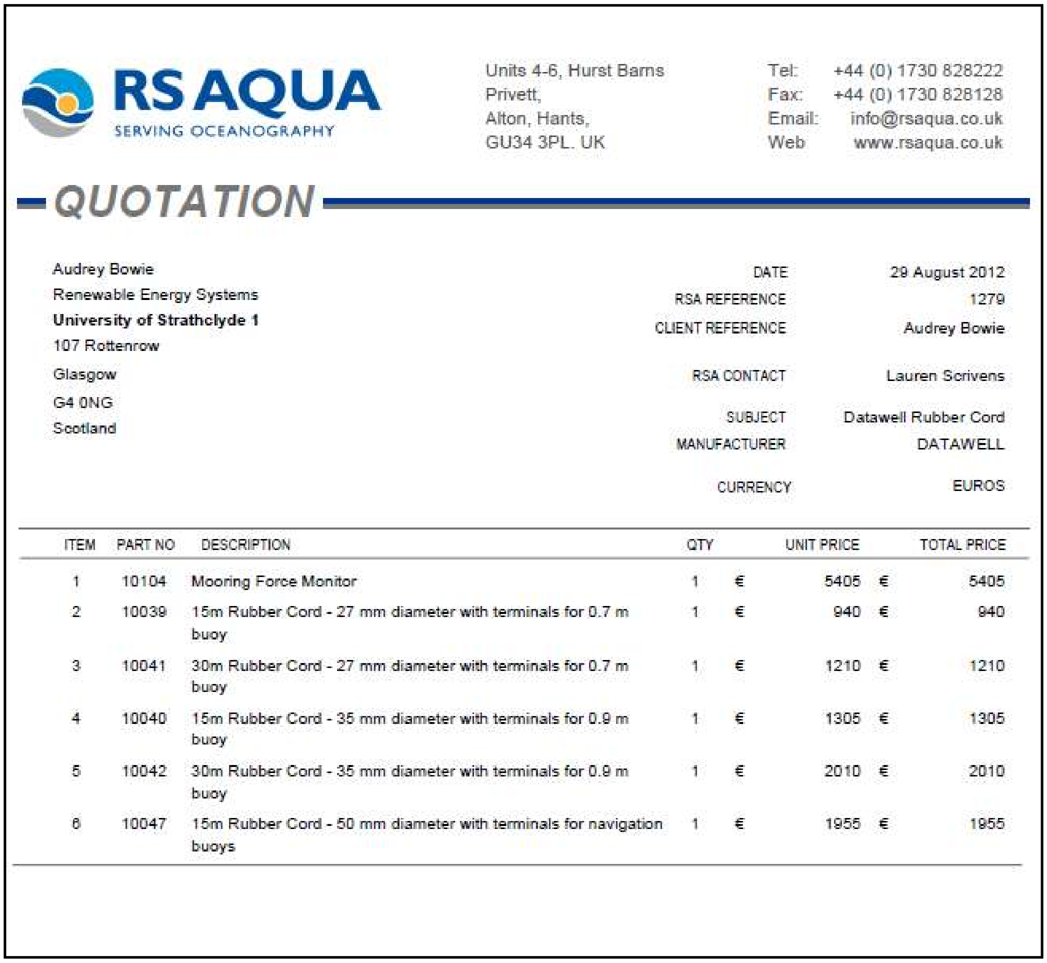
Appendices

Appendix 1



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QUOTATION

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DATE	29 August 2012
RSA REFERENCE	1279
CLIENT REFERENCE	Audrey Bowie
RSA CONTACT	Lauren Scrivens
SUBJECT	Datawell Rubber Cord
MANUFACTURER	DATAWELL
CURRENCY	EUROS

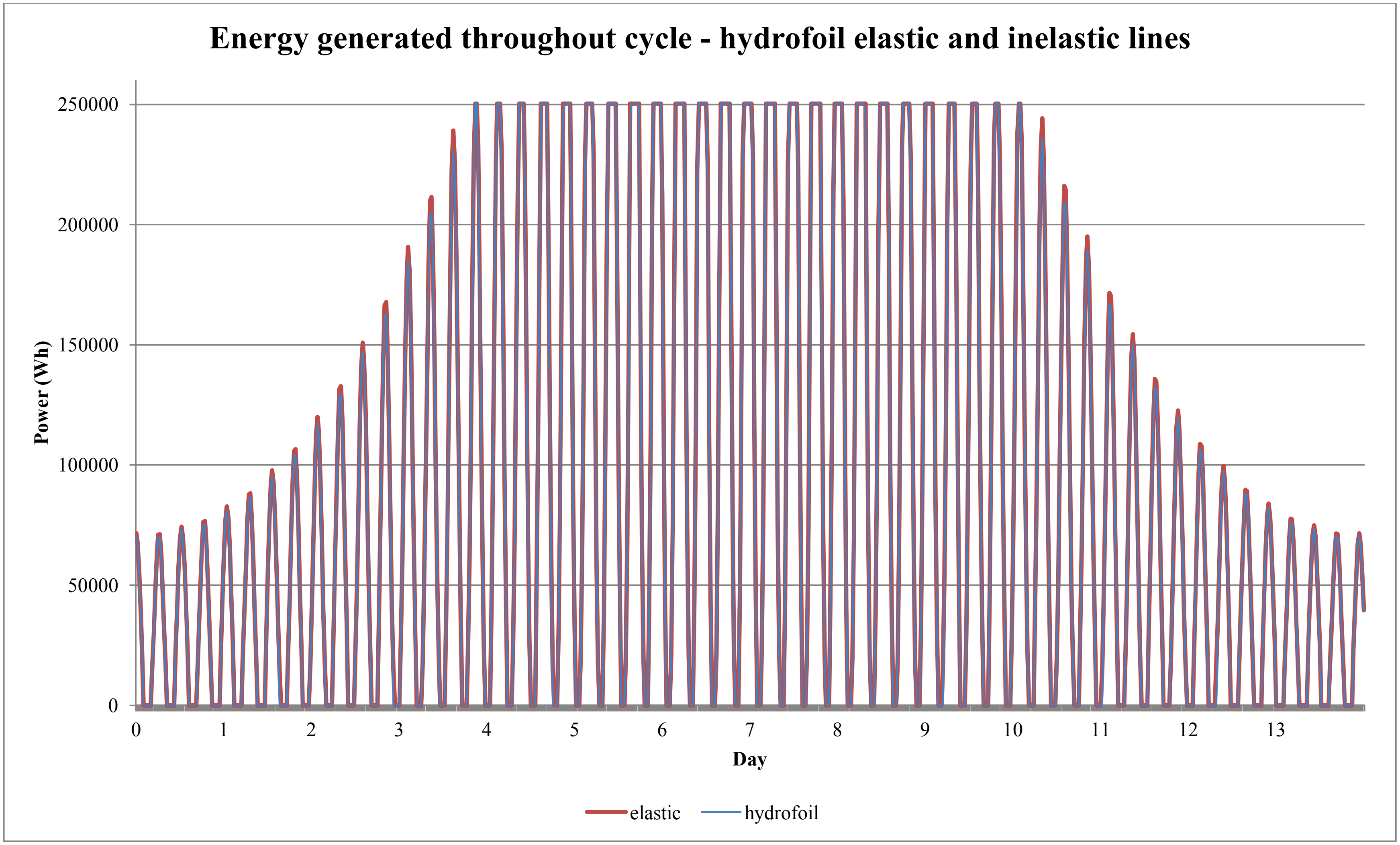
ITEM	PART NO	DESCRIPTION	QTY	UNIT PRICE		TOTAL PRICE	
1	10104	Mooring Force Monitor	1	€	5405	€	5405
2	10039	15m Rubber Cord - 27 mm diameter with terminals for 0.7 m buoy	1	€	940	€	940
3	10041	30m Rubber Cord - 27 mm diameter with terminals for 0.7 m buoy	1	€	1210	€	1210
4	10040	15m Rubber Cord - 35 mm diameter with terminals for 0.9 m buoy	1	€	1305	€	1305
5	10042	30m Rubber Cord - 35 mm diameter with terminals for 0.9 m buoy	1	€	2010	€	2010
6	10047	15m Rubber Cord - 50 mm diameter with terminals for navigation buoys	1	€	1955	€	1955

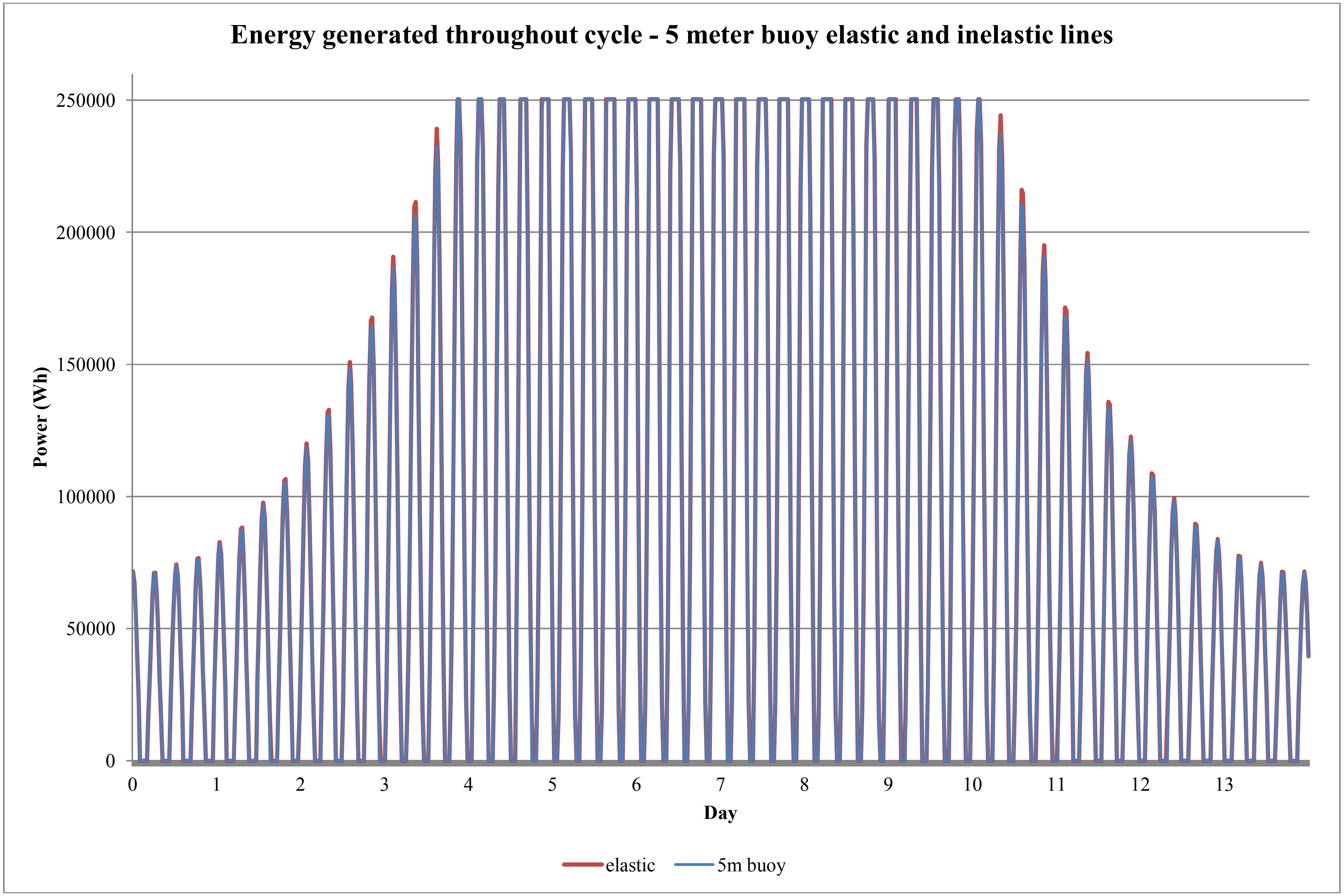
Appendix2

```
NACA 0012 hydrofoil
Drag Coefficient

--------------------------- REYNOLDS NUMBER -----------------------

ALPHA     160000    360000    700000   1000000   2000000   5000000
--------------------------------------------------------------------
    0     0.0103    0.0079    0.0067    0.0065    0.0064    0.0064

    1     0.0104    0.0080    0.0068    0.0066    0.0064    0.0064

    2     0.0108    0.0084    0.0070    0.0068    0.0066    0.0066

    3     0.0114    0.0089    0.0075    0.0071    0.0069    0.0068

    4     0.0124    0.0098    0.0083    0.0078    0.0073    0.0072

    5     0.0140    0.0113    0.0097    0.0091    0.0081    0.0076

    6     0.0152    0.0125    0.0108    0.0101    0.0090    0.0081

    7     0.0170    0.0135    0.0118    0.0110    0.0097    0.0086

    8     0.0185    0.0153    0.0128    0.0119    0.0105    0.0092

    9     0.0203    0.0167    0.0144    0.0134    0.0113    0.0098

   10     0.0188    0.0184    0.0159    0.0147    0.0128    0.0106

   11     0.0760    0.0204    0.0175    0.0162    0.0140    0.0118

   12     0.1340    0.0217    0.0195    0.0180    0.0155    0.0130

   13     0.1520    0.0222    0.0216    0.0200    0.0172    0.0143

   14     0.1710    0.1060    0.0236    0.0222    0.0191    0.0159

   15     0.1900    0.1900    0.1170    0.0245    0.0213    0.0177

   16     0.2100    0.2100    0.2100    0.1280    0.0237    0.0198

   17     0.2310    0.2310    0.2300    0.2310    0.1380    0.0229

   18     0.2520    0.2520    0.2520    0.2520    0.2520    0.1480

   19     0.2740    0.2740    0.2740    0.2740    0.2740    0.2740

   20      0.2970     0.2970     0.2970     0.2970      0.2970     0.2970
```

```
NACA 0012 hydrofoil
Lift Coefficients

-------------------------- REYNOLDS NUMBER -----------------------

ALPHA     160000    360000   700000    1000000   2000000   5000000
-------------------------------------------------------------------
  0      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

  1      0.1100    0.1100    0.1100    0.1100    0.1100    0.1100

  2      0.2200    0.2200    0.2200    0.2200    0.2200    0.2200

  3      0.3300    0.3300    0.3300    0.3300    0.3300    0.3300

  4      0.4400    0.4400    0.4400    0.4400    0.4400    0.4400

  5      0.5500    0.5500    0.5500    0.5500    0.5500    0.5500

  6      0.6600    0.6600    0.6600    0.6600    0.6600    0.6600

  7      0.7460    0.7700    0.7700    0.7700    0.7700    0.7700

  8      0.8247    0.8542    0.8800    0.8800    0.8800    0.8800

  9      0.8527    0.9352    0.9598    0.9661    0.9900    0.9900

 10      0.1325    0.9811    1.0343    1.0512    1.0727    1.1000

 11      0.1095    0.9132    1.0749    1.1097    1.1539    1.1842

 12      0.1533    0.4832    1.0390    1.1212    1.2072    1.2673

 13      0.2030    0.2759    0.8737    1.0487    1.2169    1.3242

 14      0.2546    0.2893    0.6284    0.8846    1.1614    1.3423

 15      0.3082    0.3306    0.4907    0.7108    1.0478    1.3093

 16      0.3620    0.3792    0.4696    0.6060    0.9221    1.2195

 17      0.4200    0.4455    0.5195    0.5906    0.7826    1.0365

 18      0.4768    0.5047    0.5584    0.6030    0.7163    0.9054

 19      0.5322    0.5591    0.6032    0.6334    0.7091    0.8412

 20      0.5870    0.6120    0.6474    0.6716    0.7269    0.8233
```

Appendix 3


Energy generated throughout cycle - hydrofoil elastic and inelastic lines
250000
200000
150000
100000
50000
0
Power (Wh)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Day
elastic
hydrofoil


Energy generated throughout cycle - 5 meter buoy elastic and inelastic lines
Power (Wh)
250000
200000
150000
100000
50000
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Day
elastic
5m buoy