Department of Mechanical and Aerospace Engineering

Assessing the potential for low speed tidal stream energy generation in the UK

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Abstract

This thesis assesses the potential for low speed tidal energy generation in UK territorial waters. Primary data was taken from the Marine Renewables Atlas to identify the spatial distribution of 1.8km resolution cells with spring peak tidal stream speeds between 1.01 and 2 ms^{-1}. The study used time series data from ADMIRALTY's TotalTide software to assess the potential power output of a tidal array in each cell. Potential sites for tidal arrays were then mapped on GIS software. The Significant Impact Factor method was used to find the 'technically extractable power' of a tidal energy site; the maximum capacity and yearly energy output of each site was then calculated.

The assessment found there to be a potential of 9.13 GW of technically extractable power from low speed tidal flows in the UK, with a yearly energy yield of 10.9 TWh of electricity, around 3% of UK generation. The study found that environmental constraints imposed by the Marine Protected Areas of Scotland and Marine Conservation Zones of England only reduced the capacity to 9 GW.

Sites most suitable for tidal array deployment were discussed and it was suggested that near Rathlin Island, off the coast of Northern Ireland, was one of the best places for low speed tidal energy generation due a high capacity factor and a short distance to shore and population centres. Large areas off the east coast of East Anglia were found to have the potential for 1 gigawatts of tidal arrays and also a high capacity factor, however, long distances to shore could prevent low LCoEs. It was noted that there was an overlap with operational and in development offshore wind farms in this area and it was suggested that infrastructure could be shared to reduce project costs. Many other areas with high potential generation were identified, most notably in the English Channel and off the coast of Wales and South West Scotland.

Sites with a relatively close proximity to population centres and suitable transmission infrastructure were analysed to identify if there was a suitable phase difference between sites for aggregated firm power. It was found 710 MW of firm power could be generated at spring tides, however, there are a few key sites which are essential to make this possible. The combined output of Dover, Severn Estuary and the Holy Island could generate at least 300 MW output at spring tides from a combined capacity of 1.2 GW.

Acknowledgements

Firstly, I would like to thank my supervisor Cameron Johnstone for his advice and enthusiasm shown during the project.

I would like say a big thank you to the UK Hydrographic Office for supplying the TotalTide software used to analyse tidal stream time series data, free of charge.

I would also like to thank my friends and family for their patience and support throughout the project duration.

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Nomenclature

Symbol	Meaning	Units
vM_2	M_2 constituent amplitude	ms^{-1}
vS_2	S_2 constituent amplitude	ms^{-1}
v_{Spring}	Spring peak tidal stream speed	ms^{-1}
v_{Neap}	Neap peak tidal stream speed	ms^{-1}
$v(t)$	Tidal stream velocity as a function of time	ms^{-1}
t	Time	s
T_{M_2}	Period of the M_2 constituent	Hours
T_{S_2}	Period of the S_2 constituent	Hours
U_z	Tidal stream velocity at a given depth	ms^{-1}
$\bar{U}$	Depth averaged tidal stream velocity	ms^{-1}
z	Height above the sea bed	m
h	Water depth	m
P_k	Kinetic power of a tidal stream at a given cross sectional area	W

A	Cross sectional area of water column	m^2
ρ	Density of sea water	$\frac{kg}{m^3}$
V	Tidal stream velocity	ms^{-1}
C_P	Turbine power coefficient	
P_{Ave}	Average spring peak power of a vertical cross section of the water column	$\frac{kW}{m^2}$
b	Cell breadth	m
d	Cell depth	m
D	Turbine diameter	m
Q_{Max}	Channel flow rate	$\frac{m^3}{s}$
a_o	Tidal amplitude difference	m
g	Acceleration of gravity	$\frac{m^2}{s}$
$M_{y_{Root}}$	Root bending moment of turbine blade	Nm
$F_{x_{Root}}$	Axial loading of turbine	N
$C_{F_{x_{Root}}}$	Axial loading dimensionless constant	

$C_{M_{y_{Root}}}$	Root bending moment dimensionless constant	
$Max(V_{Diamond})$	Maximum tidal diamond speed	ms^{-1}
F	Tidal diamond scaling factor	
d_{Ave}	Average depth across a channel	m
$b_{channel}$	Breadth of channel	m
C_f	Capacity factor	
D	Turbine diameter	m
A_{Swept}	Swept area of a tidal turbine	m^2
P_{Single}	Power output of a single turbine	W
P_{Cell}	Power output of a cell	W
E_{Yield}	Energy generated	kWh
$P_{Theoretical}$	Theoretical power of a tidal stream channel	W
$P_{Technical}$	Technically extractable power of a tidal stream channel	W
$\emptyset$	Phase difference	Hours
N_{Sites}	Number of sites	

1. Introduction

1.1 Background

Announced in 2019, the UK government has committed to a net zero carbon dioxide emissions target by 2050; the Scottish government an earlier target of 2045. In order to achieve this, radical changes must be made to the way people live and 'decarbonising' the energy sector is central to this. Large increases of renewable energy output in the UK in recent years are mostly due to new wind farms being added to the grid. However, the more stochastic sources of electricity generation that supply the grid, the more storage and flexibility is required. This inadvertently adds to the cost of the energy consumer, a hidden and indirect cost of wind and solar power. In Scotland old nuclear power stations are due to be shut down in 2025 without any low carbon base load generation to replace it, likely to be a big problem for a network largely based on stochastic renewables.

During the 2000s, there was a large push to develop a variety of renewable technologies in the UK, one promising technology was tidal power. *Black & Veatch (2005)* reported that the UK had approximately half of Europe's 'technically extractable tidal resource' and could provide 6% of the UK's electricity demand. Unlike wind energy, tidal power generation can be predicted very accurately due to the semidiurnal constituents driven by the gravity of the moon and the sun. This makes the electricity generated reliable and therefore very useful to the grid compared to stochastic renewable energy.

Due to large investments in wind power and slower than expected progress in developing the technology, tidal stream energy is yet to become commercially competitive and remains very expensive. There is, most notably in Orkney, companies such as SIMEC Atlantis that have plans to build large arrays that would reduce costs, however, this has not yet come to fruition.

The energy output of a tidal turbine increases proportionally with the cube of tidal stream velocity, therefore, currently developers have focused on tidal streams with a spring peak velocity of greater than 2.5 ms^{-1}. The large force exerted on the subsea turbines caused by this velocity requires strong materials and precision manufacturing to build these turbines, increasing the capital cost of array installation. This in turn is a large reason why the cost of tidal stream power has not fallen low enough to make it competitive.

1.2 Aim and Motivation

This thesis will assess the potential for low speed tidal stream generation in the UK, as a means to reduce the cost of tidal power and make it commercially viable. Opening up the potential of 'low speed' sites between 1 – 2 ms^{-1} spring peak velocities could reduce the need for such highly engineered turbines as the ones currently being developed, thus reducing the cost. Commercially viable low speed tidal generation would potentially open up many more sites that are geographically preferable to the current high speed sites of interest. The high energy sites currently considered for deployment are largely far away from population centres thus inducing large externality costs. The lack of phase diversity in the time at which energy is produced during the tidal cycle in high speed sites around the UK also prevents the matching of arrays to result in firm power.

1.3 Project Objectives and Scope

The main project objective is to assess the physical resource of low speed tidal energy in the UKs territorial waters and then discuss which sites are most suitable and how it could be best extracted. The project will investigate the advantages and disadvantages of low speed tidal power and assess the potential for commercial viability. The matching of out of phase tidal arrays will be investigated with the goal of creating a substantial firm power source.

1.4 Methodology

The study will use data collected from the DTI Atlas of UK Marine Renewable Energy Resource (Renewables-atlas.info, 2019) that contains information on water depth, tidal current speeds and distance from shore for 1.8km resolution cells in the UK's territorial waters. So that the time series for each cell over a tidal cycle can be estimated Admiralty's TotalTide software (TotalTide, 2019) is used and the tidal diamond information for many locations around the UK will be extracted. In turn, the time series data for each tidal diamond can be combined with its nearby grid cells to find tidal stream velocities over a year. The maximum 'technically unconstrained' power can then be calculated and compared to the 'technically extractable' power found using the significant impact factor method. Using a range of selection criteria, the most suitable sites for deployment will be found and discussed.

2 Literature Review

2.1 Low Carbon Energy Generation in the UK

The United Kingdom has seen a large increase of renewable energy generation over the last ten years. According to BEIS (2019), the UK generated over 20 TWh of renewable electricity in 2008 but in 2018 generated 111 TWh, accounting for 33.3% of UK electricity demand. *Figure 1* shows the breakdown of electricity generation in the UK in 2018.

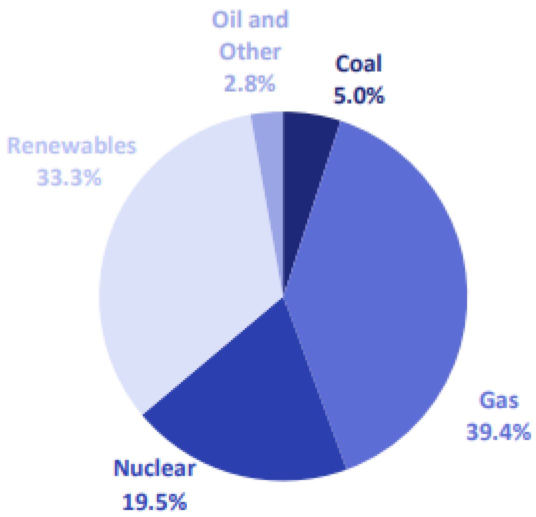

Figure 1 - Breakdown of electricity generation in the UK in 2018 (BEIS, 2019)

The UK's renewable generation is increasingly underpinned by wind power which now supplies over half of renewable supply in 2018 and many gigawatts of offshore windfarms to be constructed over the next few years will only increase this number. Whilst the technology emits no greenhouse gases upon generation, the stochastic nature of the resource puts great strain on the grid and requires extra grid flexibility to be put in place.

The solar photovoltaic industry is growing as the cost of solar panels reduces over time (IRENA, 2019) but, like wind power, the electricity output cannot be accurately predicted, however seasonal weather patterns do help the two renewable technologies complement each other. Solar PVs highest output is over the summer months and wind speeds are likely to be at their highest over the winter months in the UK.

Hydro power, the original renewable technology, has seen very limited growth in the UK over the last 50 years due to a lack of new suitable sites in mountainous areas. The amount of electricity produced by bioenergy has increased rapidly over the last decade but scepticism over the sustainability and localised air quality of the plants still persists. *Figure 2* shows the breakdown and increase of renewable generation in the UK from 2008 to 2018.

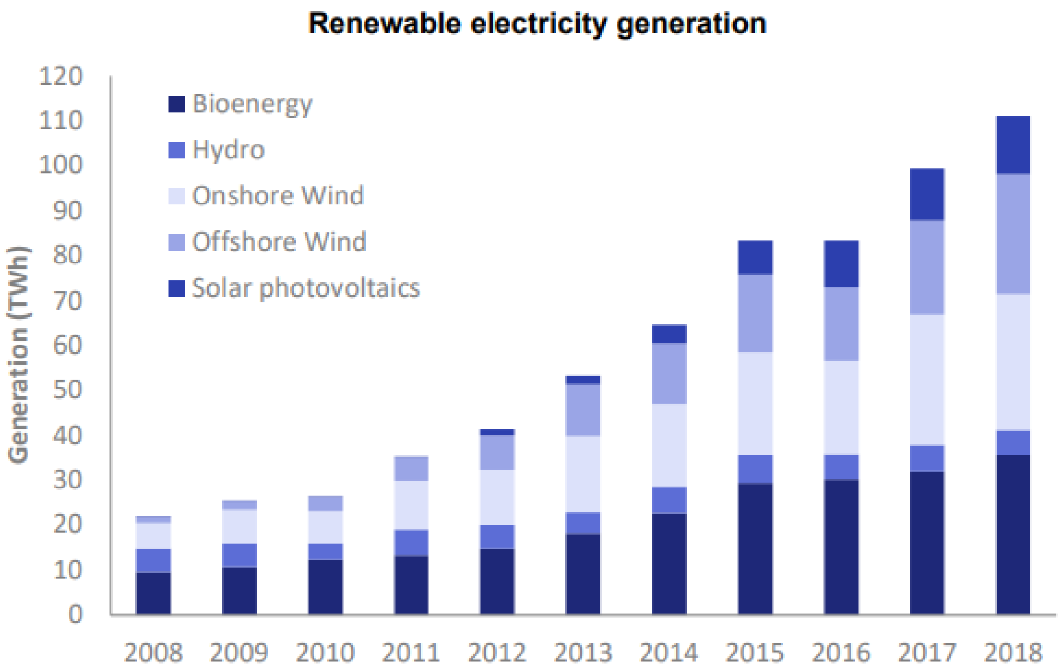

Figure 2 - Breakdown of renewable electricity generation in the UK between 2008 - 2018 (BEIS, 2019)

Nuclear power generates around a fifth of the UKs electricity generation and does so in a constant baseload form. This provides stable output to the grid, however, half of this is due to be retired by 2025 (World Nuclear Association, 2019). Only one new nuclear plant, Hinkley Point C, is due to be constructed due to a high levelised cost of energy, low public opinion, large hidden costs of decommissioning and decades long construction times.

Even though low carbon energy is increasingly supplying the UK national grid, expected increases in energy demand due to the electricification of transport and heating systems are likely to put more strain on the grid in the coming decades.

With problems like reaching renewable targets, retiring of many nuclear plants and a lack of replacement baseload, there are many issues facing the electricity grid in the

UK. In order to improve security of supply, prevent soaring electricity costs for citizens and reduce the carbon content of the electricity grid, new technologies must be considered.

2.2 Tidal Energy

2.2.1 Current State of the Tidal Power Industry in the UK

A decade ago, tidal power was heralded as the next big thing for renewables in the UK due to the vast resource and predictable supply. Ten years on and there is yet to be an operational large scale array and levelized cost of energy (LCoE) is still high. Lack of assistance from the UK government has made it very difficult for tidal power to compete with the likes of offshore wind power when winning subsidies. In 2017, tidal developers missed out (SIMEC Atlantis Energy, 2019) on a £300/MWh strike price (Marine Energy, 2019) handed out during the Contracts for Difference (CfD) auctions, in favour of supporting offshore wind.

Without having an agreed contract to help tidal power developers learn from turbine deployment and hence reduce costs, a route to market has been to difficulty to find.

Another problem for 1st generation tidal stream developers, turbines that operate in peak spring tide speeds of greater than 2.5 ms^{-1} and between 25 – 50m water depth, is the lack of suitable sites for deployment, *Figure 3* shows the sites currently investigated for 1st generation deployment. The sites in question are largely far away from population centres, therefore, high grid connection and externality costs such as upgrading transmission lines have held the industry back. The population density of the UK can be seen in *Figure 4*.

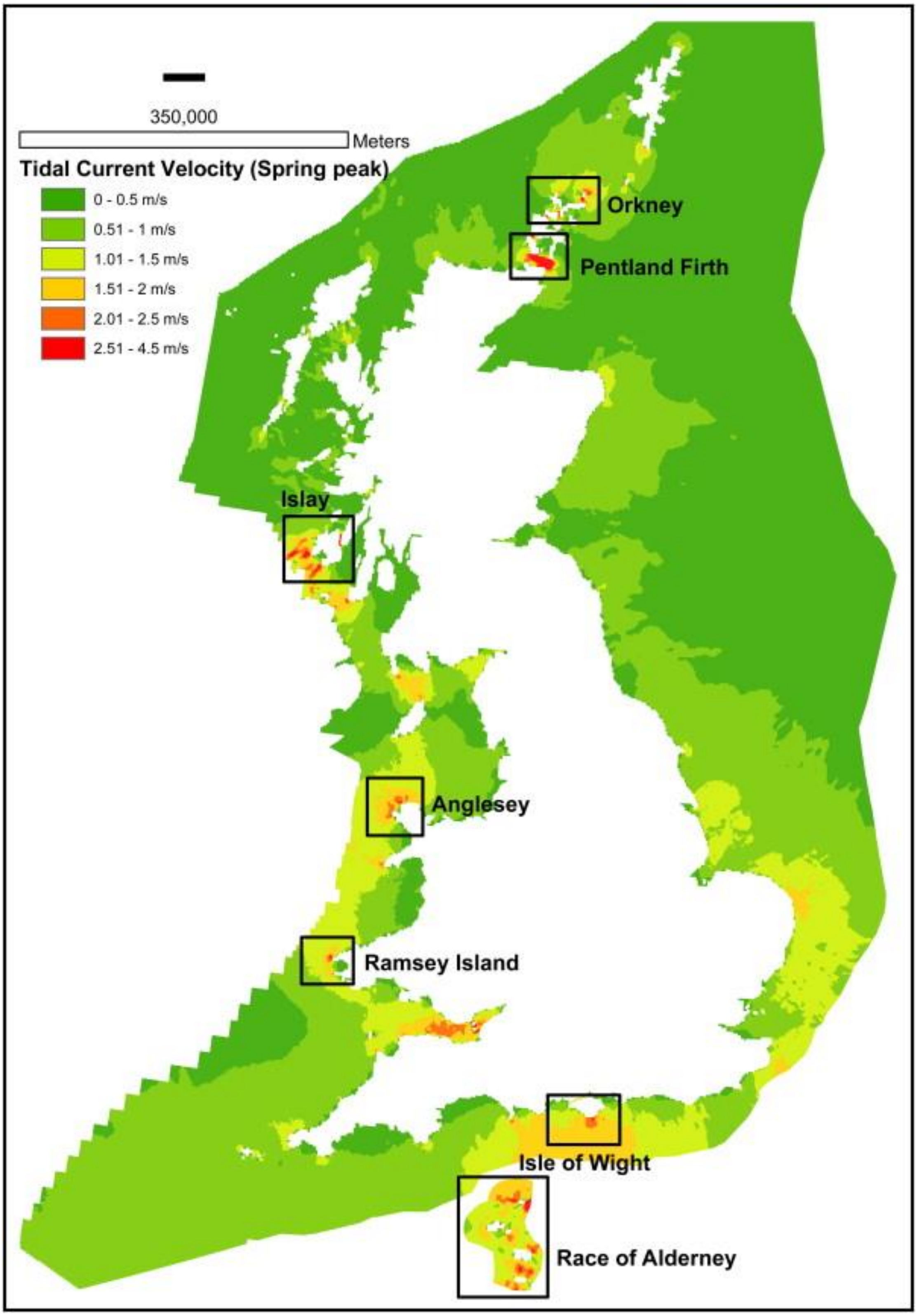

Figure 3 - Mean spring peak current and specific sites of interest. BERR Marine Atlas. ©Crown Copyright. All rights reserved 2008.

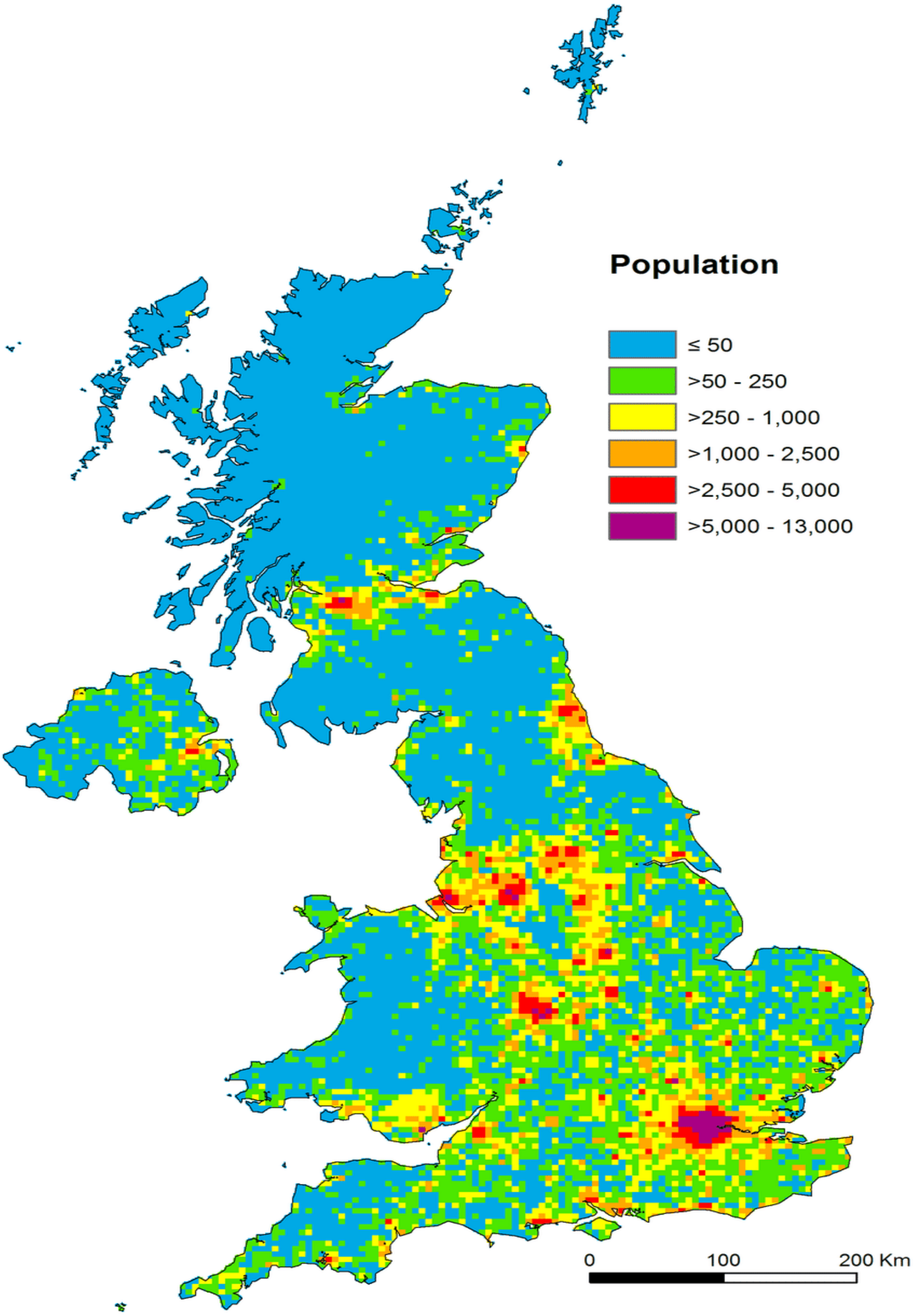

Figure 4 – Population density of the UK (Atmos-chem-phys.net, 2019)

The industry has not yet settled on an agreed best design for how best to capture the energy from tidal streams. However, there are three types of tidal stream energy capture devices in testing and operation in the UK at the moment:

1. Ground mounted tidal stream turbines - Of all the currently installed tidal turbines these are the most common but unlike wind turbines there has not been one technology that has become the generally accepted best design. Ground mounted tidal stream turbines look similar to wind turbines, but with smaller blades, mounted to the sea bed. A CAD design of these turbines can be seen in *Figure 5* below. A few developers are currently testing turbines of varying sizes, mostly at EMEC, but Atlantis' Meygen project has planning consent for a 399 MW tidal array in the Pentland Firth, Scotland. There is currently four 1.5 MW turbines already installed, making it one of the biggest tidal stream arrays in the world. Ground mounted tidal turbines mostly avoid the effects of near surface level interactions such as wind and swells, however, this does mean that the structures that support them must be large enough for the turbine to avoid the effects of a sea bed boundary layer. In turn, this means capital costs for installation are high, as is operational maintenance costs.

Figure 5 - Horizontal Axis Ground Mounted Tidal Stream Turbine (Eng.ed.ac.uk, 2019)

2. Floating tidal stream turbines – Floating tidal stream turbines are a more recently developed technology that has enjoyed success in tidal stream generation. In July 2018, one of the leading floating turbine developers, Orbital Marine Power, announced that its 2 MW device had generated 3 GWh of electricity over the past 12 months, more than the whole Scottish tidal and wave sector combined had produced over the twelve years prior (Orbitalmarine.com, 2019).

   Floating tidal turbines are usually comprised of a long central floating structure with a large retractable turbine either side. An example of this can be seen in *Figure 6*. Floating turbines have the advantage of being closer to the fastest stream in the water column, near the surface, but are more open to effects of wave and wind interaction. As the turbines are retractable they can be easily maintained but the floating structure does mean that planning permission may be harder to come by, even though some would argue that the environmental impact is less than sea bed mounted turbines. As the required planning permission makes the siting of floating structures exclusion zones, the only major depth constraint is the size of the turbines. This has the potential to open up deeper sites that are technically difficult to install sea bed mounted structures.

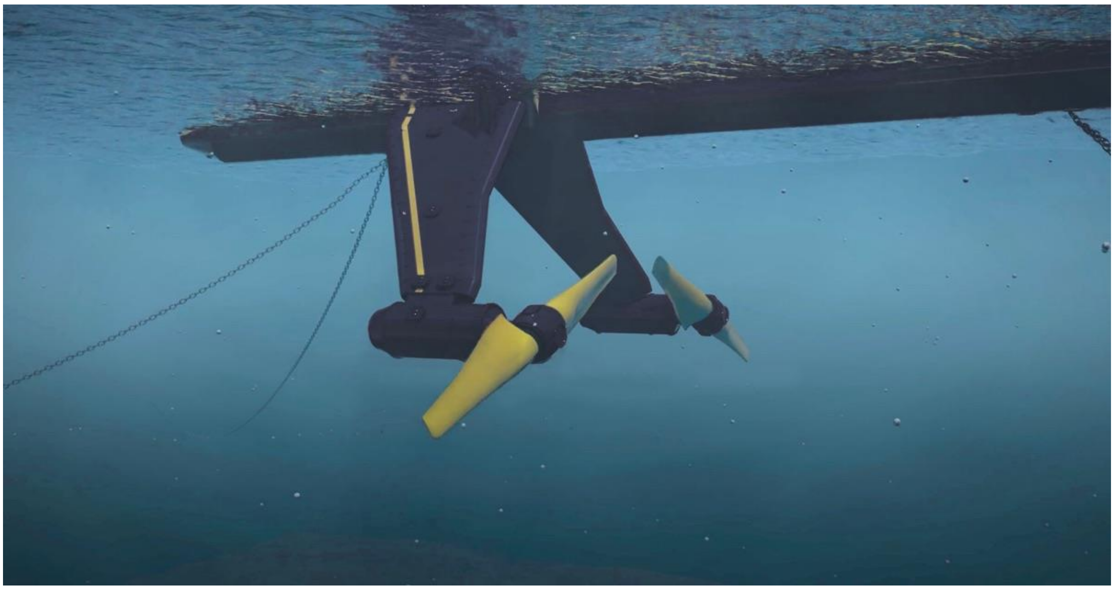

Figure 6 – Floating tidal stream turbine (Orbitalmarine.com, 2019)

3. Low speed kite tidal capture – Tidal kites are a technology in their infancy but have potential to work in lower speed tidal streams therefore opening up the opportunity of more sites than the current turbine technology. The kites harness the tides to move in a figure of eight shape whilst tethered to the sea bed, this motion turns the attached turbines quicker than if mounted on the sea bed or a stationary floating structure (Minesto.com, 2019). *Figure 7* shows the operation of the kite. A tidal kite array would however require a large area to avoid collision, therefore there are questions remaining of the energy density of the technology. Minesto are the main developers of this type of tidal energy capture and have plans to develop a utility scale deployment off the coast of Anglesey, Wales.

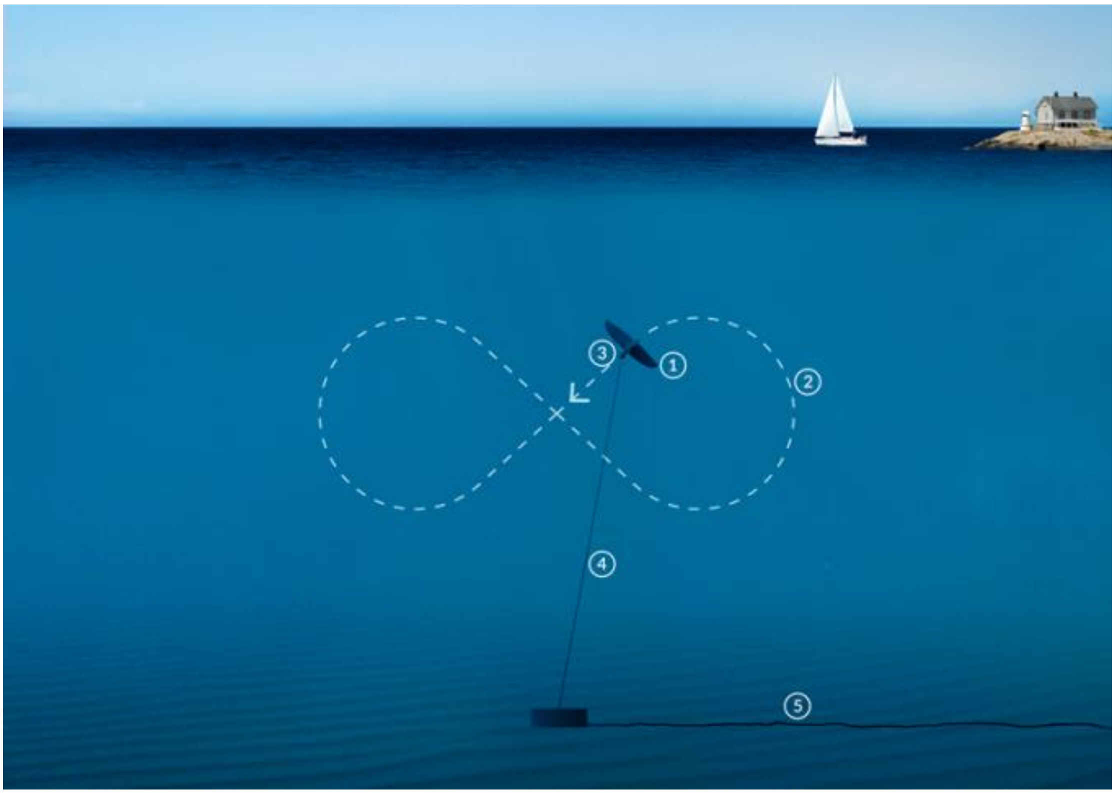

Figure 7 – Tidal kite motion (Minesto.com, 2019)

2.2.2 Tidal Power around the world

There are two major operating tidal power plants in the world. Both use tidal barrage technology, making use of differences in head heights due to tides in estuaries and works similar to a hydro powered dam. The Sihwa dam in South Korea was built in 2011 with a 254 MW capacity, making it the largest in the world (IRENA, 2014). La

Rance tidal barrage in Brittany, France was built in 1966 and to this day has an operational capacity of 240 MW, with an average annual generation of 500 GWh.

There are few places with large tidal power potential around the world, many sea bordering countries around the world do not have suitable sites. *Figure 8* shows these high energy sites worldwide.

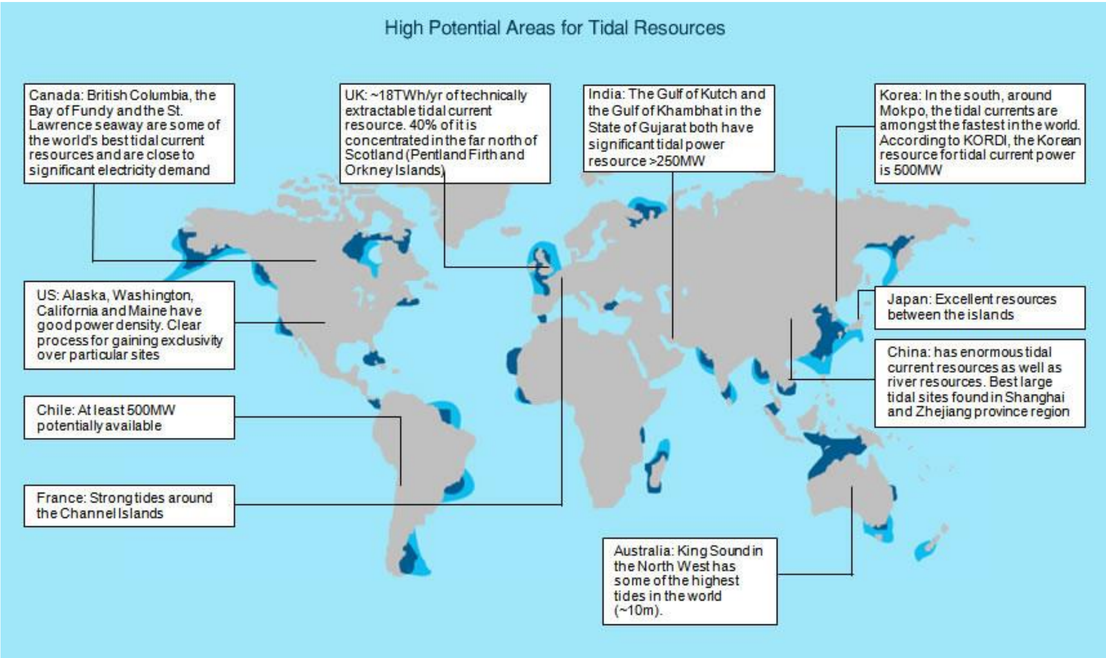

Figure 8 - High energy tidal current speed sites worldwide (Energybc.ca, 2019)

Another place where tidal stream energy devices are being tested on the same scale of the UK is Canada. FORCE (2016) report that there is a potential of 2.5 GW of extractable high energy tidal stream power in the Bay of Fundy, Nova Scotia and the government has succeeded in attracting investors and companies to test tidal turbines there, some from the UK. Like the UK there is a mixture of different types of devices being tested, but none yet at commercial scale.

2.3 UK Tidal Resource

The UK has one of the biggest tidal current resources in the world, in 2011 a study found that 1st generation devices could harness a total of 20.6 TWh of energy per year from 30 sites around the UK coast (Black and Veatch, 2011). This study accounts for a number of different factors when defining what is 'technically extractable' but the physical resource in the energy of tidal streams around the UK is much higher.

2.3.1 How tidal streams are formed

The rise and fall of tides around the world are generated by the gravitational pull from the sun and the moon. The forces cause the sides of the Earth closest and farthest away to the moon to bulge, thus creating differences in sea level height due to the daily rotation of the Earth. This bulging effect can be seen in *Figure 9*.

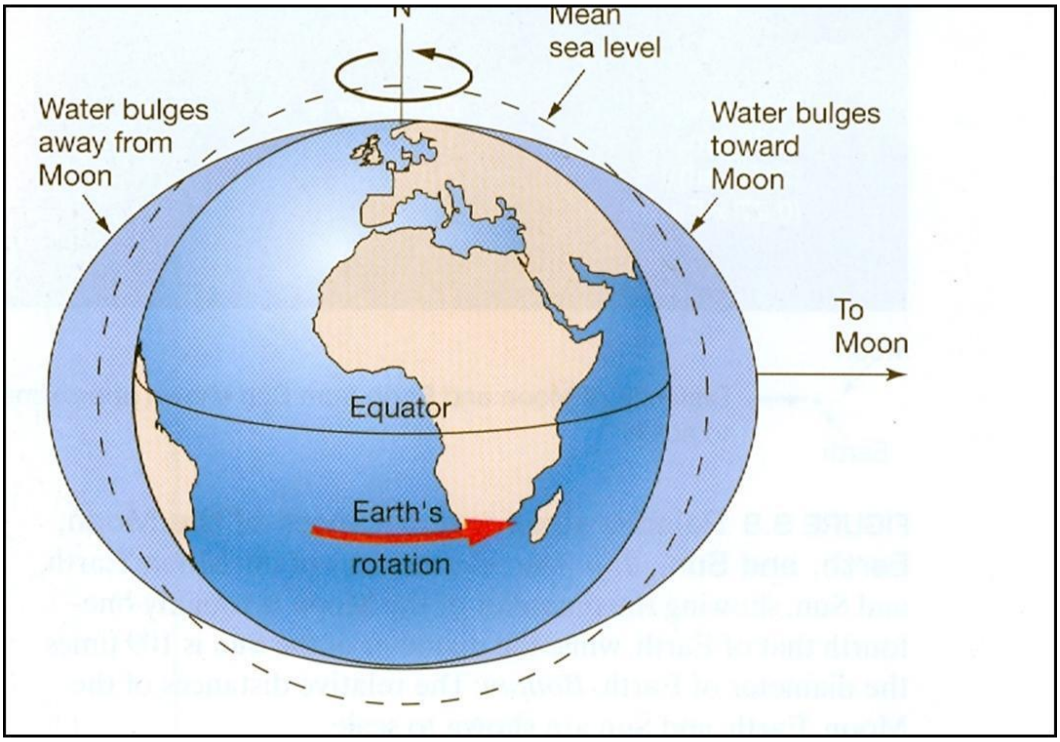

Figure 9 – How the gravitational pull of the moon deforms the seas around the earth (Byrd, 2019)

The changing sea levels between high and low tide mean that water rushes from one place to another. In large bodies of water, such as the Atlantic Ocean, the speed of water moving from high to low tide and vice versa is usually very low. However, when the flow of water is squeezed through channels, tidal currents accelerate and can be substantial. Bathymetric conditions of the sea bed must be right in order for a tidal current to be fast enough for energy generation. It must be noted that high and low tide happen at different times around the UK coast. Tidal waves propagate mostly due to the Coriolis force created from the spinning of the Earth, causing the cyclonic rotation of the tide to flow counter clockwise around the UK (Neill and Hashemi, 2018).

High and low tide occur roughly twice a day in most places, meaning there are usually four peaks of electricity generation per day. This is due in part because the Earth spins a full rotation once every 24 hours, therefore, twice during the day a specific point on Earth will be in the direct line of the moons gravitational forces. This creates flooding, movement of low to high tide, and ebbing, movement of high to low tide, a graph of which can be seen for the Scilly Isles in *Figure 10*.

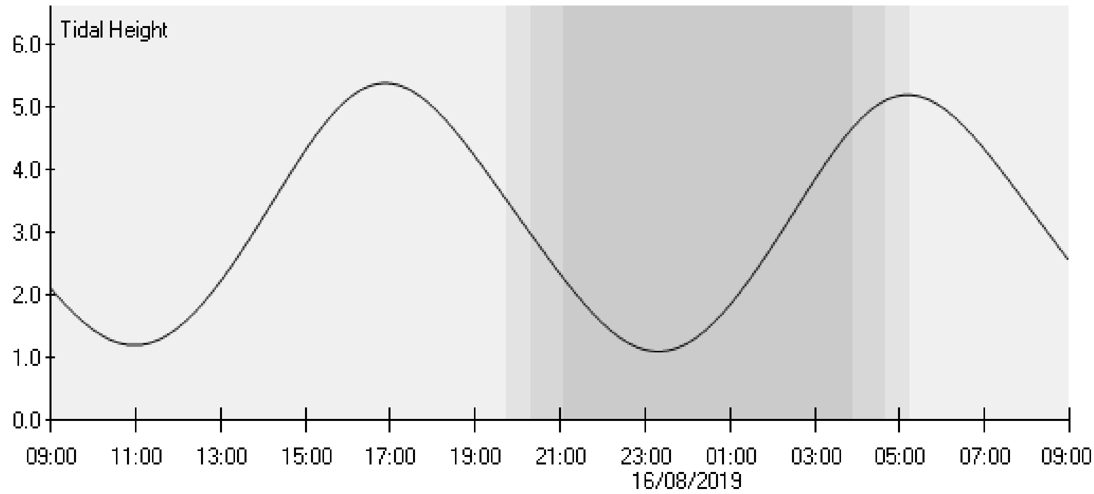

Figure 10 - Graph of tidal heights throughout a day in the Scilly isles, UK (TotalTide. 2019)

The tidal stream speed loosely correlates to the change in tidal range with respect to time. This can be seen in *Figure 11*.

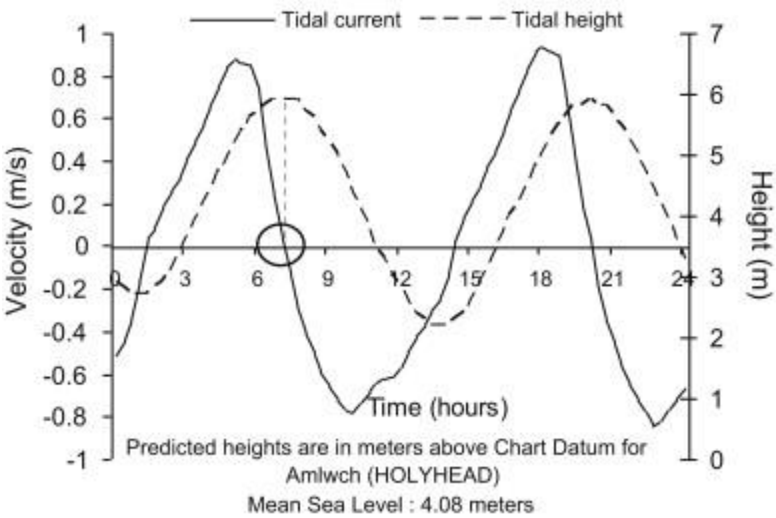

Figure 11 – Graph of tidal heights & tidal streams for a day in Amlwch, Wales (Iyer et al. 2013)

2.3.2 Spring and neap tides

A full tidal cycle occurs roughly every 14.77 days in the UK (Neill and Hashemi, 2018). Once within this tidal cycle, the tidal forces are at their strongest when it is either a new moon or a full moon, this is called a spring tide. The syzygy of the moon, Earth and sun combines all the gravitational forces to their strongest, thus forcing the biggest range in tides. The tidal forces during this bi-monthly cycle are at their smallest when there is a quarter moon and therefore the moons gravitational forces are acting perpendicular to that of the suns, this is called a neap tide.

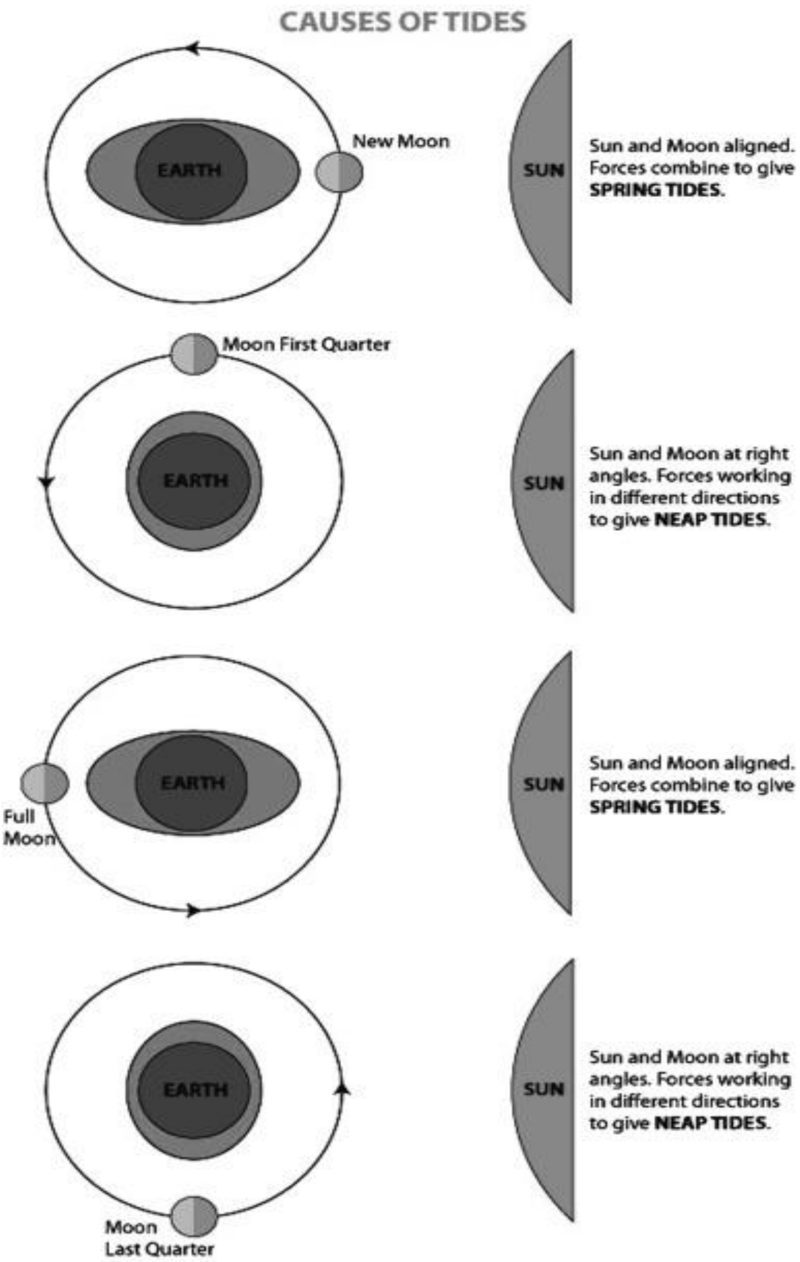

Figure 12 – How the spring and neap tides are formed (Hassan et al. 2012)

This pattern means that the peak tidal stream speeds at the flood and ebb of a tide can change drastically over the 14.77 day tidal cycle, usually a spring tides tidal stream speed is about double that of a neap tides speed. The spring neap difference in tidal range can be seen in *Figure 13*.

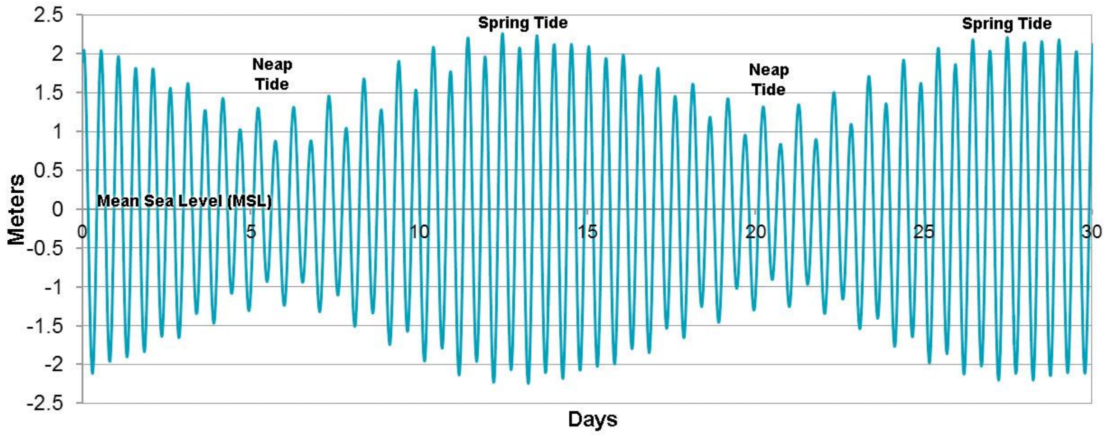

Figure 13 – Example of change in tidal range during spring and neap cycle (Geologycafe.com, 2019)

2.3.3 Modelling the tides

Modelling the movement of the tides is complex, as many different factors such as bathymetry and atmospheric conditions are at play. However, the harmonic motion of the tide due to gravitational forces can be estimated using constituent parts based on the periods of various harmonic interactions.

The rotation of the Earth with respect to the moon, is represented by the principle lunar semi-diurnal constituent, M2, the period of which is given by 12.42 hours. The other main constituent, S2, represents the rotation of the Earth with respect to the sun and therefore has a period of 12 hours. To model the predicted tidal stream speed at any given time, both constituents must be assigned an amplitude to include how the respective gravitational forces affect the tidal stream speed. These amplitudes, vM_2 and vS_2, can be estimated if the spring peak and neap peak stream speeds are known for a location, shown in *Equations 1 & 2*.

$$vM_2 = \frac{v_{Spring} + v_{Neap}}{2}$$

Equation 1

$$vS_2 = \frac{v_{Spring} - v_{Neap}}{2}$$

Equation 2

These constituents can then be used in *Equation 3* to find the tidal stream speed.

$$v(t) = vM_2 \cos\frac{2\pi t}{T_{M_2}} + vS_2\, cos\frac{2\pi t}{T_{S_2}}$$

Equation 3

Where t is the time at any given point and T_{M_2}& T_{S_2} are the M_2 and S_2 periods, respectively.

It is important to note that the tidal stream speed varies with the depth of the water column. Due to the frictional boundary layer created by the sea bed, the tidal stream speed tends to increase closer to the surface. The generally accepted way to calculate the tidal stream speed at any depth within the water column is using *Equation 4* (Neill and Hashemi, 2018).

$$U_z = \overline{U}(\frac{z}{0.32h})^{1/7}$$

Equation 4

Where $\overline{U}$ is the depth averaged tidal stream speed (ms^{-1}), z is the height above the sea bed (m), h is the water depth (m). Whilst this equation gives a good approximation of how the boundary layer affects tidal stream speeds, above surface interactions like wind and waves can affect the speed of tidal streams, especially near the surface.

2.3.4 Extracting energy from the tides

The instantaneous power of a tidal stream can be calculated using *Equation 5*.

$$P = 0.5A\rho V^3$$

Equation 5

Where A is the cross sectional area (m^2), ρ is the density of sea water ($\frac{Kg}{m^3}$) and V is the speed of the tidal stream (ms^{-1})

The power that can be converted from the energy in the tides using a horizontal axis tidal turbine can be calculated using *Equation 6.*

$$P = 0.5C_P A\rho V^3$$

Equation 6

Where C_P is the power coefficient, A is the swept area of the tidal turbine (m^2), ρ is the density of sea water ($\frac{Kg}{m^3}$) and V is the speed of the tidal stream (ms^{-1}).

The power coefficient, C_P, can be defined as the ratio of the power captured to the power of the water flowing through a cross sectional area. It must be noted that the turbine efficiency is limited by the Betz limit of 0.593, much in the same way wind energy is. The value of C_P usually used to calculate the power output of a tidal turbine is 0.4 (Thake, 2015). The swept area of a tidal turbine is dependent on the radius of its turbine blades, seen in *Figure 14.*

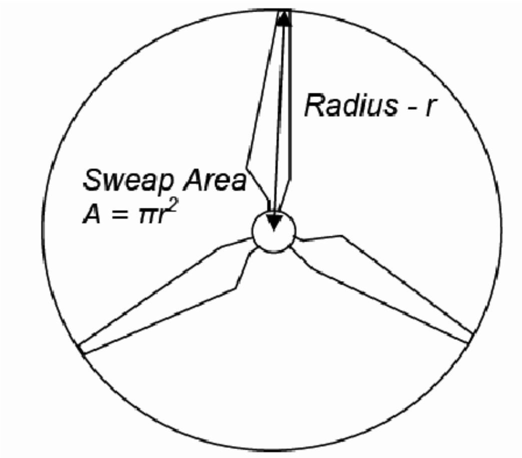

Figure 14 – Swept area of tidal turbine (Ghenai and Sargsyan, 2010)

The interaction between tidal turbines and how they affect wake propagation is still not fully known, partly because there are few full-scale operational tidal arrays. However, to avoid wake interaction European Marine Energy Centre (EMEC) standards suggest using a lateral spacing of 2.5 times the rotor diameter between each turbine hub and a downstream spacing of ten times the rotor diameter (Legrand, 2009). Most papers suggest using a larger lateral spacing, for example Iyer et al.(2013) use a lateral spacing of three times the diameter. A diagram of this can be seen in *Figure 15*.

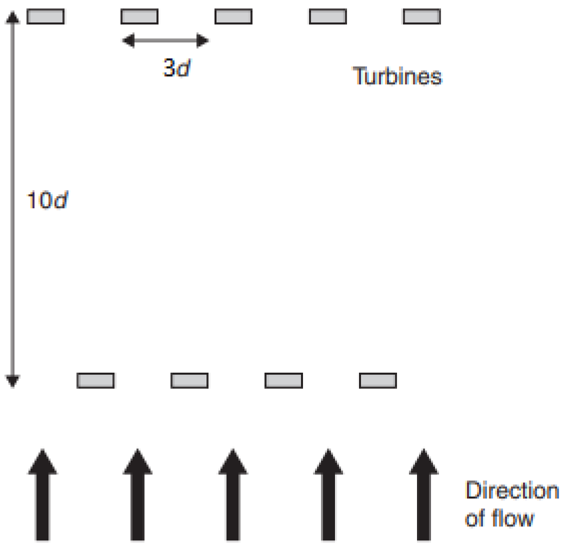

Figure 15 - Layout of turbines to avoid interference (Legrand, 2009)

2.3.5 Tidal resource assessments

Tidal resource assessments of the UK have been undertaken since the 1970s but the methods to quantify this resource and potential for energy generation has greatly evolved since. (Blunden and Bahaj. 2007)

Blunden and Bahaj (2007) discuss how estimates of the maximum total practically extractable tidal energy resource of the UK has reduced over time. The main resource assessments before 2007, were conducted by Black and Veatch (2005) and estimated an average resource of 2.1GW +/- 0.6. This method included the Significant Impact Factor, SIF, calculating the technically extractable resource as 20% of the energy flux of a channel, sometimes though removing certain channels so the flux was not counted twice and reducing the SIF to closer to 10% on some occasions. Phase I of the study identified the extractable and available energy for < 2.5 ms^{-1}sites to be 774 GWh/y. On closer inspection of the study, only sites greater than 1.5 ms^{-1} were assessed and hence when channels were measured to calculate maximum energy flux, they were only measured across the distance of the local sites greater than 1.5ms^{-1}. This does not take into account a large proportion of the low energy sites, therefore it is likely an underestimate of the low speed tidal energy resource. Phase II of the study agreed with this prediction, stating that velocity ranges of < 2.5 ms^{-1}accounted for 20.1% of total resource, up from 3.5%.

The report was updated in 2011 (Black and Veatch, 2011) and involved a new method of calculating the extractable resource. The study sorted the main sites into three categories, hydraulic current, tidal streaming and resonant basin depending on which hydrodynamic mechanism was most prevalent. *Table 1* shows how the theoretical and technical resources were calculated using this method.

	Expression of theoretical limit of tidal current energy harvesting.	Expression of technical limit of tidal current energy harvesting.	Hydrodynamic response limiting energy harvesting.
Hydraulic current	$P_{Theoretical} = 0.2\rho g Q_{\max} a_o$	$P_{Technical} = 0.086\rho g Q_{\max} a_o$	Velocity reduction
Resonant basin	$P_{Theoretical} = 0.2\rho g Q_{\max} a_o$	$P_{Technical} = 0.033\rho g Q_{\max} a_o$	Downstream tidal range
Tidal streaming	$P_{Theoretical} = 0.16\rho g Q_{\max} a_o$	$P_{Technical} = 0.020\rho g Q_{\max} a_o$	Downstream tidal range

Table 1 – Updated method for calcuting the extractable tidal energy from a channel. (Black and Veatch. 2011)

Where Q_{max} is the flow rate through a channel (m^3/s), ρ is the density of sea water, g is the acceleration of gravity (m^2/s) and a_o is the tidal amplitude difference (m).

The 2011 report had a much heavier focus on the economics of tidal energy and gave a range of total practical resource from 10.3 TWh/y in the pessimistic case to 30 TWh/y in the optimistic case. Different tidal velocity bins of practical resource were not shown in the report, hence, it is hard to assess the maximum suggested technically extractable energy for low speed tidal energy.

2.3.6 Suitability for electricity generation

Apart from shutdown due to maintenance, the output of tidal stream turbines can be predicted long into the future, however, due to the harmonic motion of the tide flooding and ebbing, there are normally parts of the semidiurnal tidal cycle where the output of a turbine is negligible. From a grid management perspective, this is far more useful than stochastic wind power and it means that power plants can be alerted in advance as to when they will be required to pick up the slack. This does though require extra backup capacity on the grid to make it viable, thus increasing the cost of domestic energy prices. From an environmental point of view, the amount of energy produced from tidal power would displace that of a more greenhouse gas emitting form of energy generation. However, the capacity required to meet demand when tidal arrays are not producing power is likely to be dispatchable gas power stations in the UK but also increasingly battery or pumped hydro storage.

Studies in the past have looked at the most efficient way of matching tidal arrays with battery or pumped storage hydro to create a base load power source. Whilst this can smooth out fluctuations in power output, the energy market does not usually pay a higher price for smoother electricity output, therefore not making it favourable for an energy developer to take on this extra cost. Efforts to make base load power from tidal power are also hindered by the difference in power outputs between spring and neap tides. A large difference in the tidal stream speeds during a bi-monthly tidal cycle can produce very little power output around neap tides; this difference is exaggerated because tidal stream power output is related to the cube of tidal stream speed.

One way of producing smoother overall power output to the grid is the phasing of tidal stream arrays so that the aggregated power output has less fluctuations. The UK's geography makes it a good place to do this. Flooding and ebbing of tides around the coast occur at very different times thanks to a long coastline. For example, it can be high tide at one point on the south coast of England and low tide at another. *Figure 16* shows these differences; the black circles highlight areas under consideration for high speed tidal stream generation.

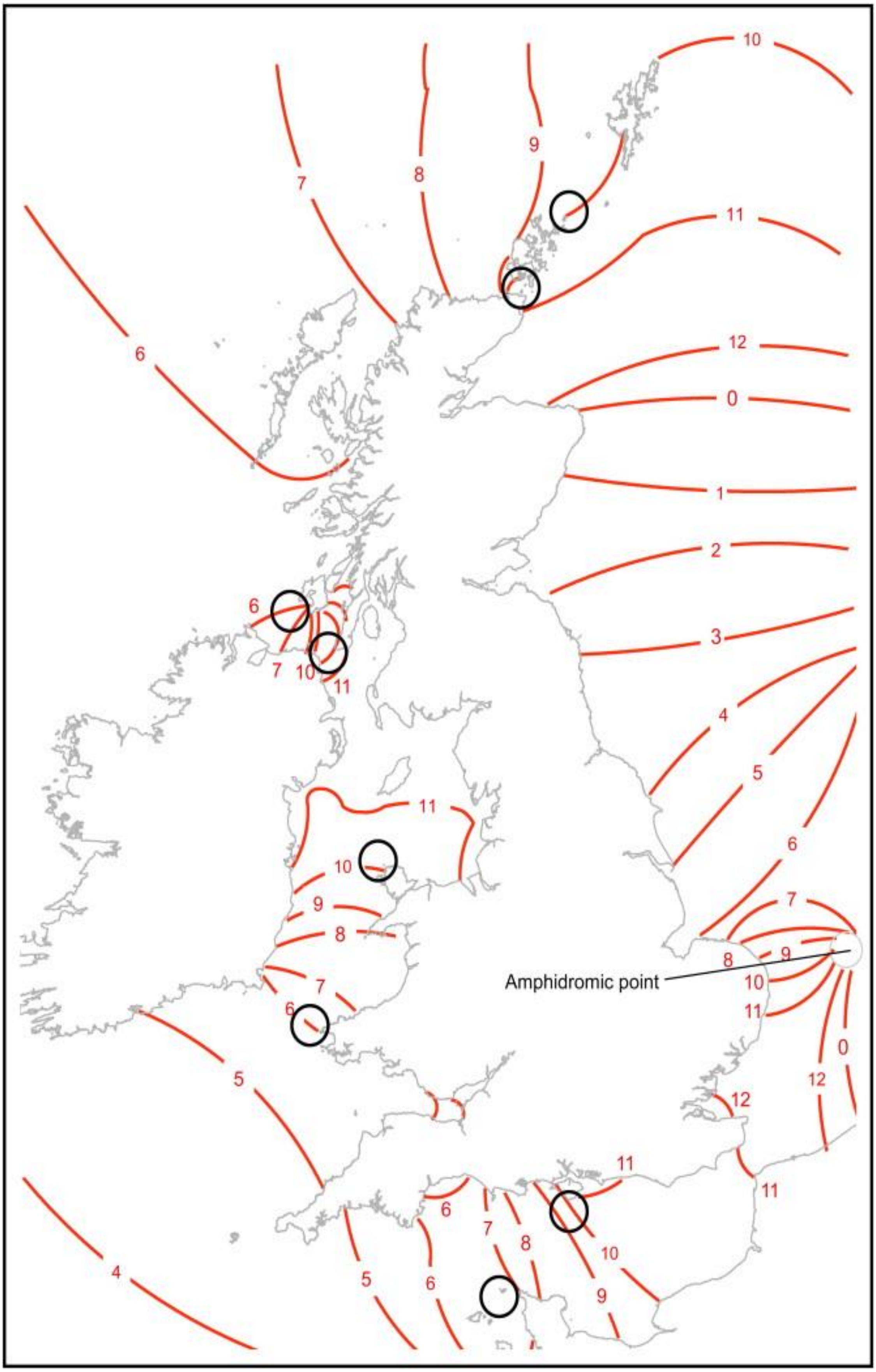

Figure 16 - Phase difference around the UK, Iyer et al. (2013)

Clarke et al. (2006) report the phasing of tidal stream turbines can create firm power when sites are selected that are out of phase with each other's tidal cycle and pumped storage can smooth remaining fluctuations further. However, due to the lack of high energy tidal sites around the coast of the UK, Iyer et al. (2013) find that firm power cannot be produced using 1st generation tidal energy sites. As shown earlier in *Figure 3*, there are few high energy sites and even though they are spread out across the UK, they are largely in phase with one another, shown in *Figure 17*.

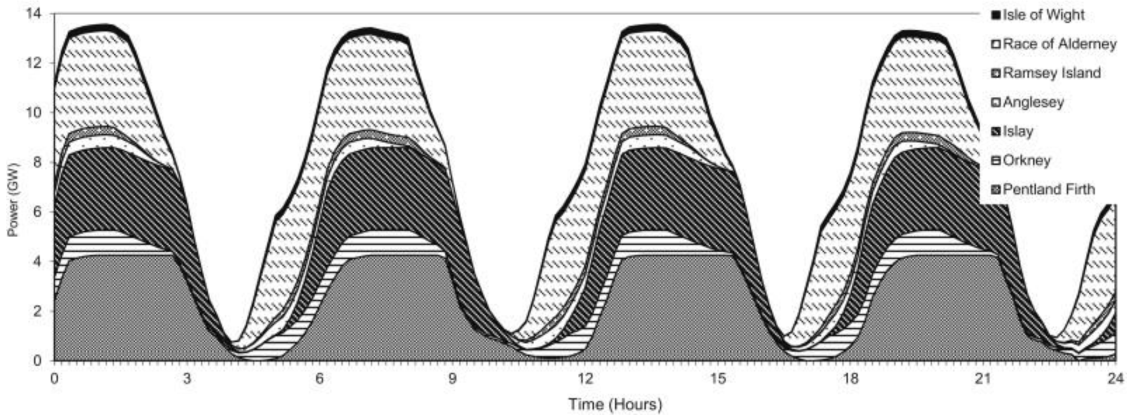

Figure 17 - Aggregated power output of high energy sites around the UK. Iyer et al. (2013)

To address this problem, this thesis will investigate how diversity in low speed tidal power sites phase could produce firm power.

2.3.7 Environmental impact

The impact of tidal stream turbines on the environment is yet to be fully known because of the lack of large scale deployment, however, Frid et al (2012) argue that they have a direct effect on marine life due to the alteration of water flows. They mention that the technology is a lot less harmful to local wildlife than tidal barrages that dam off whole estuaries and the low angular speed of tidal stream turbines make it highly unlikely for marine mammals to be injured by them. Environmental impacts will vary from site to site and the way in which a turbine is installed and decommissioned will be a factor.

Government proposed Marine Conservation Zones (England & Wales) and already implemented Marine Protected Areas (Scotland) are designed to reduce the impact on the environment from various human factors and industries. It is likely that marine energy deployment may be restricted in these areas and perhaps could be no development zones.

It is important to note that every renewable technology has lifecycle emissions associated with its manufacture, transportation and installation. Tidal turbines are no different, one of the first commercially deployed tidal turbines Seagen was estimated to have lifecycle emissions of 15g CO_2/kWh, comparable to that of large wind turbines (Douglas, Harrison and Chick, 2008).

2.4 Research into Low Speed Tidal Generation

To date there has been very little academic research into low speed tidal energy generation and P Fraenkel (2002) suggests that a minimum of 2 ms^{-1} spring peak flow is necessary for a tidal stream site to be economically viable. However, this suggestion does not take into account that lower stream speeds would not require such expensively manufactured turbine blades. It must be noted that many papers investigating the phasing of high energy sites and discussing the long term viability of the tidal power industry mention the need to implement tidal arrays at low speed sites (Iyer et al., 2013 & Lewis et al., 2015).

Alcérreca-Huerta et al (2019) assess the low speed potential resource off the Coast of Cozumel Island, Mexico but do not investigate the economics into extracting it and Black and Veatch (2011), one of the most cited UK resource assessments only assesses the economics of 1st generation tidal power production.

Boehme (2006) states that 43% of the cost of tidal power is the turbine blade and 25% the foundations, therefore, large cost savings can be made using cheaper turbines. One paper discusses using sites of low speed tidal energy but goes on to investigate the how using ducted turbines can funnel the water flow to make it faster (Tarver et al. 2015). It is discussed that ducted turbines can increase drag forces, therefore, requiring the increased strength of foundations of the turbine. Turbines tested at high energy sites in the past have included ducts, however, most currently tested turbines have stopped using them. This thesis will focus on the idea of reducing the complexity of low speed tidal energy extraction as much as possible, hence, ducted turbines will not be considered.

There are certain places in the UK and around the world where realising the potential of low speed tidal power could reap large rewards for developers. There are, for example, ocean currents that move constantly, giving the potential for base load power output. Only cheaper turbines can meet this potential though, as the speeds at which they flow would not make it financially viable for high energy turbines to operate.

2.5 Low Cost Turbines and Commercial Potential

"*The vast majority of tidal turbine blades are made from glass fibre or hybrid glass/carbon fibre composites and some also use composites for other parts of the turbine structure. To date, blade manufacturing has focused on high-cost, low volume prototype blades."* – Flanagan et al. (2015).

The design of tidal turbines is quite different to that of wind turbines, mostly due to the vastly different fluid densities of air and seawater and velocities of fluid flow. Hence, tidal turbines have much shorter blades.

Much research has been done on optimising the manufacture and design of tidal turbines for performance in high energy tidal sites. Low torque, low solidity turbines constructed of cheaper materials, possibly polymers, could facilitate large cost reductions when compared to conventional high energy turbines. To reduce the torque applied to the turbine, without reducing the power output, ways of increasing the tip speed ratio must be considered. Encarnacion et al. (2019) discuss the advantages and disadvantages of this and offer a design specification that reduces torque by 33% but power output by only 8% in low speeds.

The predicted reduction in material costs is in part due to governing equations of blade root bending moment and axial loading.

$$M_{y_{Root}} = 0.5\rho\pi r^3 v^2 C_{M_{y_{Root}}}$$

Equation 7

$$F_{x_{Root}} = 0.5\rho\pi r^2 v^2 C_{F_{x_{Root}}}$$

Equation 8

Where $M_{y_{Root}}$ is the root bending moment of the turbine, $C_{M_{y_{Root}}}$ is a dimensionless constant related to the root bending moment of a turbine, $F_{x_{Root}}$ is the axial force acting on the turbine, $C_{F_{x_{Root}}}$ is a dimensionless constant related to the axial forces acting on turbine.

These equations explain why the root bending moment and axial forces increase proportionally to the square of tidal stream velocity. A dimensionless graph of relationship can be seen in *Figure 18.*

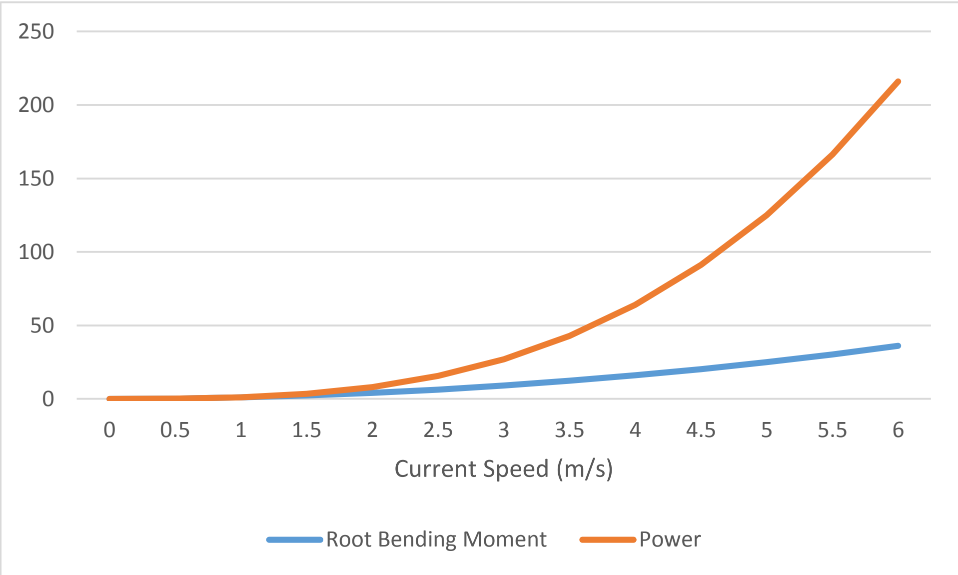

Figure 18 – Dimensionless graph showing the relationship between current speed, root bending moment and power output

This graph shows why better material characteristics such as young's modulus are required for tidal turbines operating in high energy sites than those which operate in low energy sites. This suggests that the young modulus of a turbines material designed to operate at 2 ms^{-1}would be a quarter of the same size turbine at 4 ms^{-1} flows. According to Boehme (2006), turbines and foundations account for 43% and 25%, respectively, of the total capital cost of tidal energy per kW. However, a more recent study suggests that the cost of the turbine and structure amounts to 30-50% of the capital cost (Astariz, Vazquez and Iglesias, 2015). Whilst it is out with the scope of this project to estimate, with a degree of certainty, the cost of manufacture and installation of low speed tidal turbines, it is reasonable to suggest these costs can be greatly reduced by deployment in low energy sites.

2.6 Island community tidal arrays

Whilst the goal of this study is largely to study how low speed tidal power could make a contribution to the UK national grid, it is anticipated that there will be tidal sites found that are suitable for energy generation but far away from strong grid connections. If this is the case, arrays could be deployed to feed in to nearby island communities micro grids.

Many islands in the UK, mostly off the west coast of Scotland, are either entirely cut off from the national grid or have weak connections, thus requiring them to come up with innovative solutions to meet their electricity demands. In the 21st century, many have turned to small-to-medium scale wind turbines, battery systems and back up diesel generators. Whilst this a good interim solution, the predictability of tidal power could reduce costs and encourage islanders to use electricity in innovative ways when the tide is flooding or ebbing. With increased technology for storing heat, the bi-daily cycle of cycle of tidal could work well in conjunction with heat pumps and the storing of heat for homes.

As commercial tidal power is still in the early stages of development and costs are high, island supplying tidal power is not yet common. However, North Yell, Shetland Isles, holds the title for the world’s first community owned tidal turbine (Scottish Government News, 2019), with electricity exported to the grid in 2014.

3 Methodology

3.1 Marine Renewables Atlas

Finding the physical resource and technically extractable tidal energy from national scale tidal systems, requires big datasets usually derived by computer model and validated by measuring on site conditions. As such a task is out with the scope of this project and many models already have acceptable and accessible data, two different software packages were used to facilitate suitable estimation of resource.

The primary data used in this study is taken from the marine renewables atlas which is free to use and publically available. The Marine Renewables Atlas (Renewables-atlas.info, 2019) is a website that displays data produced by the Proudman Oceanographic Laboratory POL CS20 tidal model (Iyer et al. 2013) in the form of a GIS layer over the UK territorial waters. The data contains tidal characteristics such as spring peak tidal stream speed and bathymetry data for each 1.8km resolution grid square around the UK. It must be noted that values given for spring and neap peak tidal stream speed and water depth are an average over the 1.8 km resolution grid square, therefore, estimated values of the technically unconstrained power available are likely to be an overestimation due to varying bathymetry. The spring peak tidal steam speeds are also a depth averaged value of the water column.

3.1.1 Grid cell selection criteria

The data was downloaded from the Marine Renewables Atlas website so it could be interrogated in other software platforms. This study was only looking at low speed tidal power, hence, all cells with spring peak speeds of over 2 ms^{-1}were removed from the study as were speeds of 1 ms^{-1}or less as it was assumed from which the potential extractable energy would be too little. The result of this was 26,233 grid cells that meet the criteria of 'low speed.'

Minimum and maximum depth constraints were also added to only assess cells that were economically and technically viable using current installation technology.

Any cell with a depth of less than 25m was removed so that tidal turbines would avoid collision with boats; UK regulations state that any underwater development must be at least 8m below sea level in order to avoid conflict with the hull of boats. It would be technically possible for small turbines to be installed in depths of less than 25m, however, this would require special planning permission and it is unlikely that large scale commercial developments would site arrays at these depths.

A maximum depth constraint of 50m was used for this assessment because of the high cost of turbine installation at larger depths and structures required for the turbine to avoid the seabed boundary layer would not be economically viable at this stage.

This left 7708 grid cells that met the criteria for assessment of potential energy resource.

3.1.2 Maximum theoretical power per cell

The maximum theoretical power for a single cross section of the water column in a cell was calculated using the value for average spring peak power, P_{Ave} (kW/m^2), associated with each grid cell and multiplying it by the cell depth and cell width, 1.8km. The resultant value will be a large overestimate of the potential resource of that cell but is a good spatial indicator of where the areas of high kinetic energy are. There is potential in the future, if technology allows, that larger turbines could be deployed that cover a much larger cross sectional areas in deep water.

Equation 9 shows how the maximum theoretical power of a cross sectional area was calculated.

$$P_k = P_{Ave}bd$$

Equation 9

Where P_{Ave} is the average spring peak power (kW/m^2), b is is the breadth (m) of the grid cell and d is the depth (m).

3.1.3 Technically unconstrained farm method

In what is an important part of the analysis, it is vital to perform what is a best estimate of the maximum energy that could be extracted, using current technology, from low speed tidal energy cells within the studies boundaries. This method calculates the maximum power that can be extracted from a tidal stream, without considering the feedback from other turbines, this will be called the ‘technically unconstrained power’. The maximum technically unconstrained power of each grid cell was calculated as follows:

- IF Depth => 25m & Depth < 30m Then D = 12m
- IF Depth => 30m & Depth < 40m Then D = 15m
- IF Depth => 40m & Depth =< 50m Then D = 20m

Different turbine diameters were used to ensure the maximum possible energy was extracted. Once each cell was assigned a turbine diameter, the swept area for a single tidal turbine can be calculated:

$$A_{Swept} = \pi \left(\frac{D}{2}\right)^2$$

Equation 10

Where D is the turbine diameter (m)

Next, the number of turbines that could fit into each cell could be calculated. Using a slightly more conservative lateral spacing of 3 diameters between turbines than EMECs standard discussed in Section 2.3.4, in line with the Iyer et al.(2013) method, the maximum number of turbines that could fit in a single 1800m x 1800m grid cell is dependent on the turbine diameter. It is important to note at this point, that this is a highly idealised placement of turbines and in reality, local bathymetry would dictate how many turbines could be placed in an array. *Table 2* contains the calculated number of turbines per grid cell for each diameter size.

Turbine diameter (m)	Number of turbines per cell
12	750
15	480
20	270

Table 2 – Number of turbines per cell dependent on turbine diameter

The maximum power output of a single tidal turbine in any grid cell can be calculated using *Equation 11*.

$$P_{Single} = 0.5 C_P A_{Swept} \rho {V_{Spring}}^3$$

Equation 11

Where V_{Spring} is the spring peak speed assigned to each grid cell (ms^{-1}).

The density of sea water is assumed to be 1025 (kg/m^3) and the power coefficient is assigned the value of 0.4. It is noted that the turbines are assumed to have yaw technology, therefore, angle of tidal stream was not taken into consideration.

The maximum power output of each grid cell can be calculated using *Equation 12*.

$$P_{Cell} = 0.5 C_P A_{Swept} \rho {V_{Spring}}^3 n$$

Equation 12

Where n is the number of turbines associated with each grid cell.

It is important to note that if the number of turbines per cell is dynamically driven by the turbine diameter, which it is in this case, then the power output per cell is the same for each size.

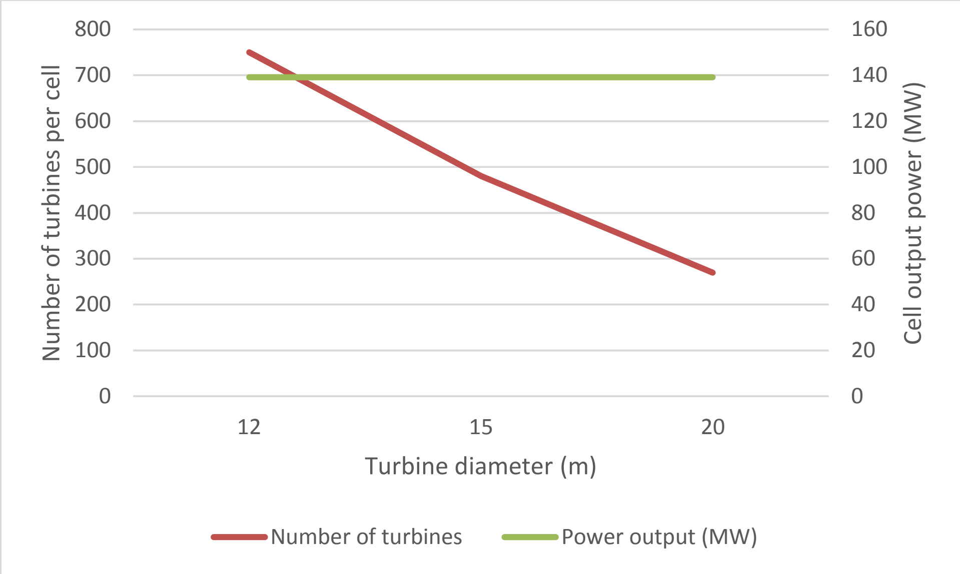

Figure 19 – How the turbine diameter changes the no. turbines per cell

3.2 Time Series

The maximum technically unconstrained power output of each cell was calculated using *Equation 13*, however, this is a snapshot of the potential power at the fastest tidal streams of the tidal cycle. As tidal stream speeds differ greatly throughout a semidiurnal cycle and also between spring and neap tide, *Equation 13* must be altered to find the power output of a grid cell at any given time.

$$P_{Cell} = 0.5 C_P A_{Swept} \rho (V(t))^3 n$$

Equation 13

Where $V(t)$ is the velocity of tidal streams with respect to time (ms^{-1})

This section will discuss how accurate tidal stream time series data was assigned to all 7708 grid cells, analysed in this study.

The Marine Renewables Atlas cell data contains the average spring and neap peak speeds of each grid square. These values are only representative of several short time periods a month, therefore it is important to incorporate time series data to give an overview of the potential energy available during the period of a spring neap tidal cycle. Time series data also facilitates the matching of tidal stream sites to generate overall firm power output. Theoretically, a tidal streams velocity varies with time sinusoidally, in reality bathymetry, ocean currents and many other local factors prevent any such harmonic symmetry.

3.2.1 TotalTide

The ADMIRALTY software package TotalTide gathers together all tidal diamonds and UK hydrographic office data to predict tidal stream speeds at any given time at certain locations all around the globe. An example of the interface that can be seen from the software package is shown in *Figure 21*.

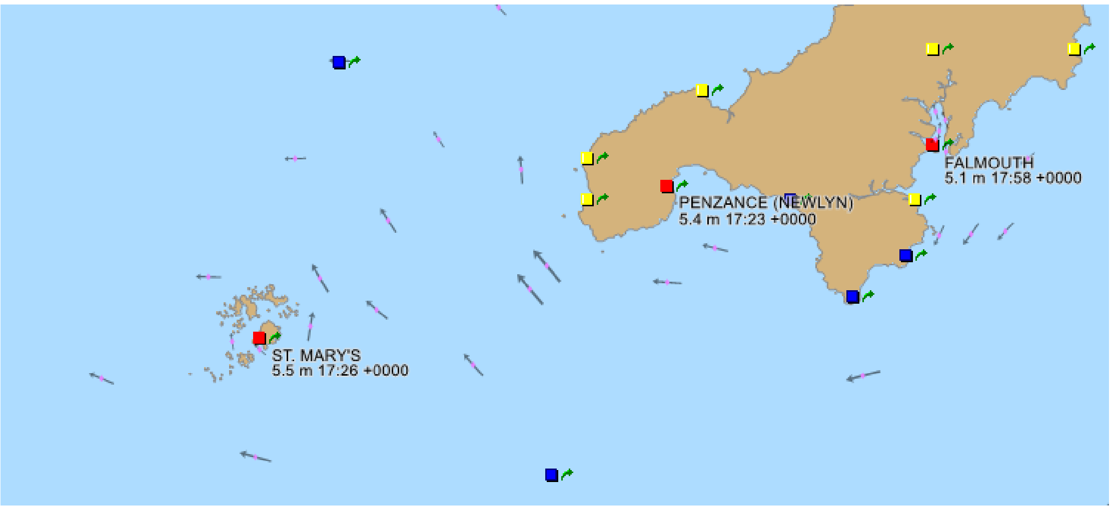

Figure 20 – Screenshot of the TotalTide software view of the Scilly Isles and Cornwall

As there are many tidal diamond locations around the UK, the time series data generated by TotalTide gives a good approximation of how the velocity of a site varies with time. The data's smallest iteration of 5 minutes gives a good degree of accuracy, however, it must be noted that speeds of over 1 $ms^{-1}$are only displayed with one decimal place, hence, creating a round uncertainty. *Figure 22* shows a screenshot of the time series data displayed for tidal diamond SN000Q off the coast of the Scilly Isles.

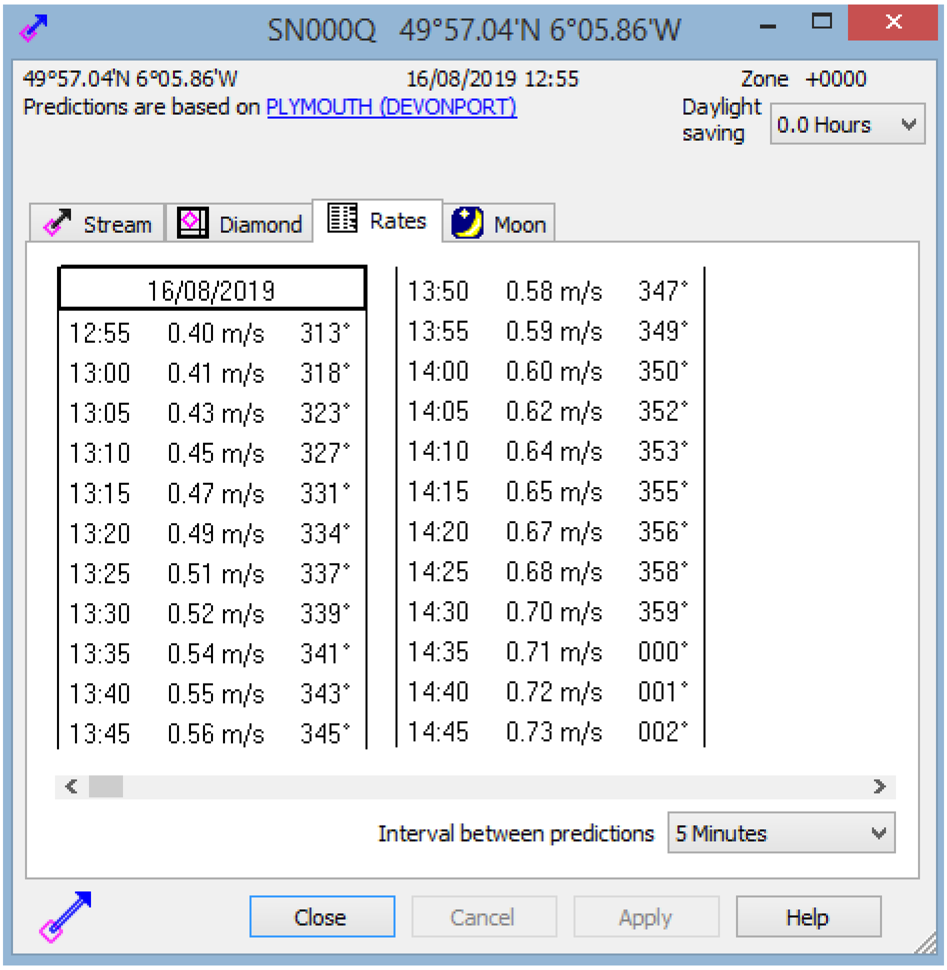

Figure 21 – Screenshot of the time series data for tidal diamond SN000Q

Using GIS software, each grid square that met the conditions discussed in Section 3.1, was matched with its closest possible tidal diamond and therefore assigned appropriate time series data. It must be noted that the matching of appropriate tidal diamonds was a manual process and whilst this was done multiple times to strive for accuracy, it cannot be guaranteed that human error may skew the results slightly. The time series data for each grid cell was then sized using a scaling factor calculated using *Equation 14.*

$$F = \frac{V_{Peak}}{Max(V_{Diamond})}$$

Equation 14

Where $Max(V_{Diamond})$ is the maximum tidal stream speed of the tidal diamond time series data (ms^{-1}).

The scaling factor for each cell was then used to multiply the time series data in which each cell was assigned.

An example of the process of assigning the correct tidal diamond to a cluster of grid cells and then scaling them to match the Marine Renewables Atlas data can be seen below for the Scilly Isles:

1. The 7708 grid cells identified by the speed and depth range criterions were highlighted in the Marine Renewables Atlas software.

2. Clusters of these squares, such as the Scilly Isles, shown below in *Figures 23 & 24*, were identified.

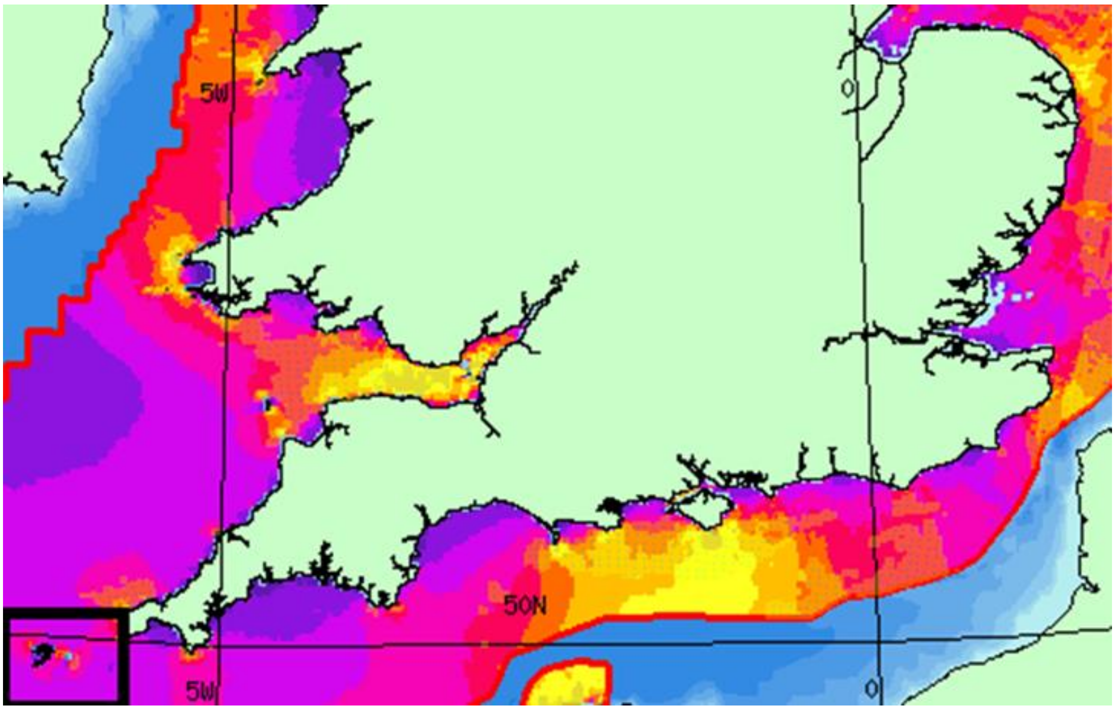

Figure 22 - Location of the Scilly Isles in relation to mainland Britain

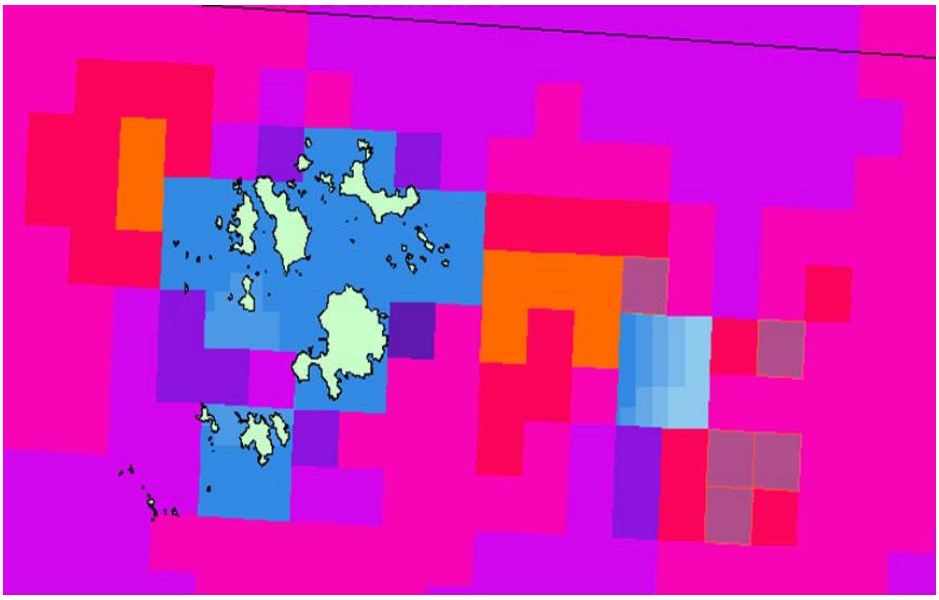

Figure 23 - Five grid squares highlighted in Scilly Isles

3. The closest tidal diamond was identified on TotalTide and its coordinates were marked on the GIS software to check the locations closely matched.

Figure 24 - Location of tidal diamond in relation to potential tidal stream sites

4. Velocity time series data of the tidal diamond, in five minute iterations, were taken from TotalTide and the scaling factor for each of the five grid cells was calculated using *Equation 14*.

5. Each grid cells associated scaling factor was then used to alter the tidal diamonds time series to appropriately model how the velocity changes with time in that cell. The five grid cells modelled time series output over 12 hours can be seen in *Figure 26* along with the SN000Q tidal diamond data.

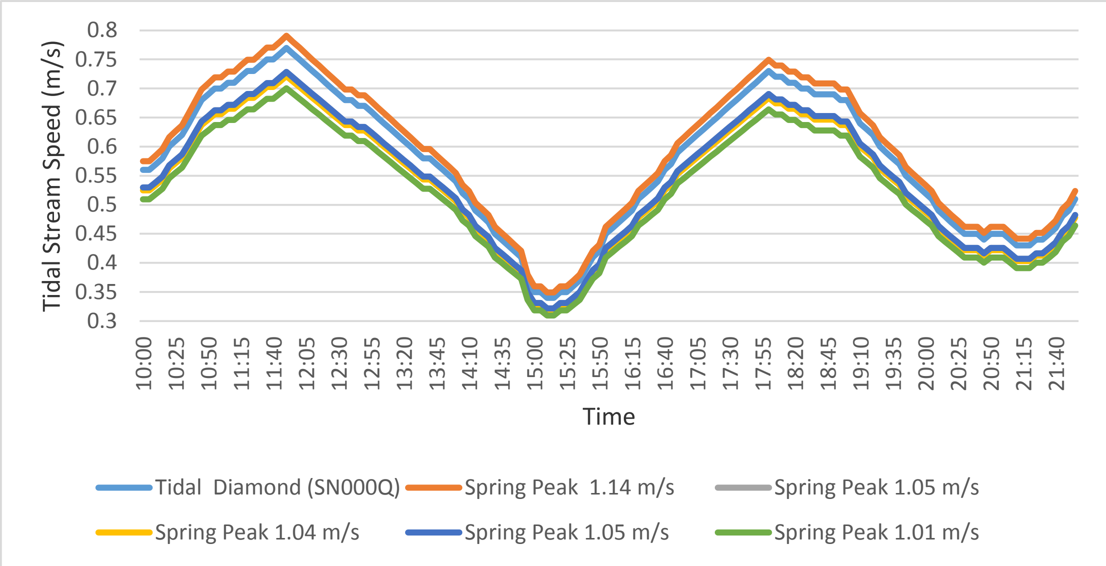

Figure 25 - Example graph of how Scilly Isles tidal stream speed varies with time over a 12 hour period

This was done for all 7708 grid cells using the data of 85 parent tidal diamonds.

Once the time series data for each grid cell is known, the capacity factor and power output at any given time can be calculated using *Equation 12*. *Figure 26* shows the predicted power output and tidal current speed over a day for a grid cell in the Scilly Isles.

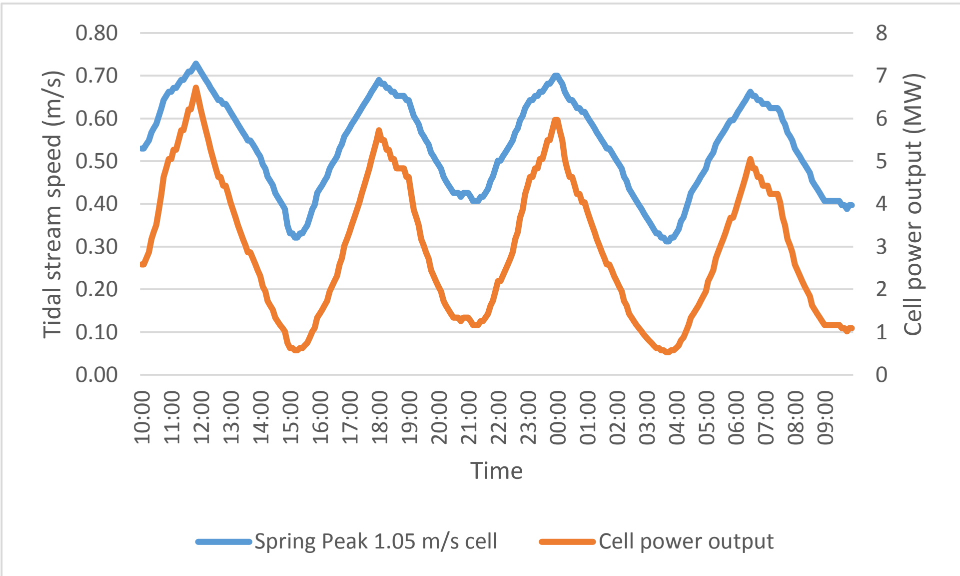

Figure 26 – Example power output of a cell over a 24h period

3.2.2 Technically unconstrained yearly energy yield

Equation 15 shows how the technically unconstrained yearly energy yield of each grid cell was calculated using *Equation 14*. 14.77 days is the period of the spring neap cycle.

$$E_{Yield} = \frac{365}{14.77} \int_{0}^{14{,}77\ days} 0.5 C_P A_{Swept} \rho (V(t))^3 n\, \delta t$$

Equation 15

The value generated from *Equation 15* is the maximum energy that can be technically extracted for each grid cell, it does not take into account any loss of energy as a result of maintenance down time or feedback effects from other nearby tidal arrays. When interrogated using GIS software the yearly energy yield of each cell is a good spatial indicator of sites with the technical potential to develop low speed tidal generation.

3.2.3 Significant impact factor

Whilst the method used to calculate the technically unconstrained potential cell capacities and energy yield is useful and gives a good indication of the possible energy extraction from single cells, it fails to consider the maximum theoretical energy that flows through a channel. The technically unconstrained method does not take into account how the extraction of energy will affect the available energy, therefore when multiple sites capacities are added, it can produce a gross over estimate of the possible resource. Black and Veatch (2005) developed a method to counteract this, called the SIF, Significant Impact Factor. The method involves calculating the maximum kinetic energy of a channel and multiplying it by 20% to find the 'technically extractable' energy that can be converted without reducing energy extraction further downstream or adversely affecting the environment by drastically reducing the flow of the tides. *Equation 16* shows how the maximum theoretical resource of a channel was calculated.

$$P_{Average} = d_{Ave} b_{channel} P_{Ave}$$

Equation 16

As discussed in Section 2.3.5, twice, an updated version of the report revised this method, first by reducing the SIF at certain sites dependent on their local hydrodynamics, then by calculating the resource differently depending on the sites dominant hydrodynamic mechanism.

These methods require complex numerical modelling of local site hydrodynamic flows and categorisation of individual channels mechanics, both of which were considered outside the scope of this thesis. Whilst the SIF method was revised because of the complex nature tidal stream sites, Black and Veatch (2015) states that ‘significant work would be required to estimate an updated SIF’ for sites not considered in the top ten high energy sites. It should also be mentioned that the 20% SIF method used in Phase I of Black and Veatch (2005) produced results that fall well within the upper and lower limits of the Black and Veatch (2011) study.

The 20% SIF method is not perfect, but will facilitate a first estimation of low speed tidal energy resource on a national level. Detailed site specific calculation of tidal energy resource would be required in any case; the SIF method will highlight key sites suitable for low speed energy generation.

The 20% SIF method was conducted for all major channels and sites where low speed cells were located. An example of how the SIF method was used to calculate the maximum extractable energy of the channel between the Mull of Galloway and the Isle of Man is shown below.

1. A line directly perpendicular to the tidal stream flow was implemented on the GIS software across the width of fastest section of low speed cells. All cells that were in contact with this line were selected.

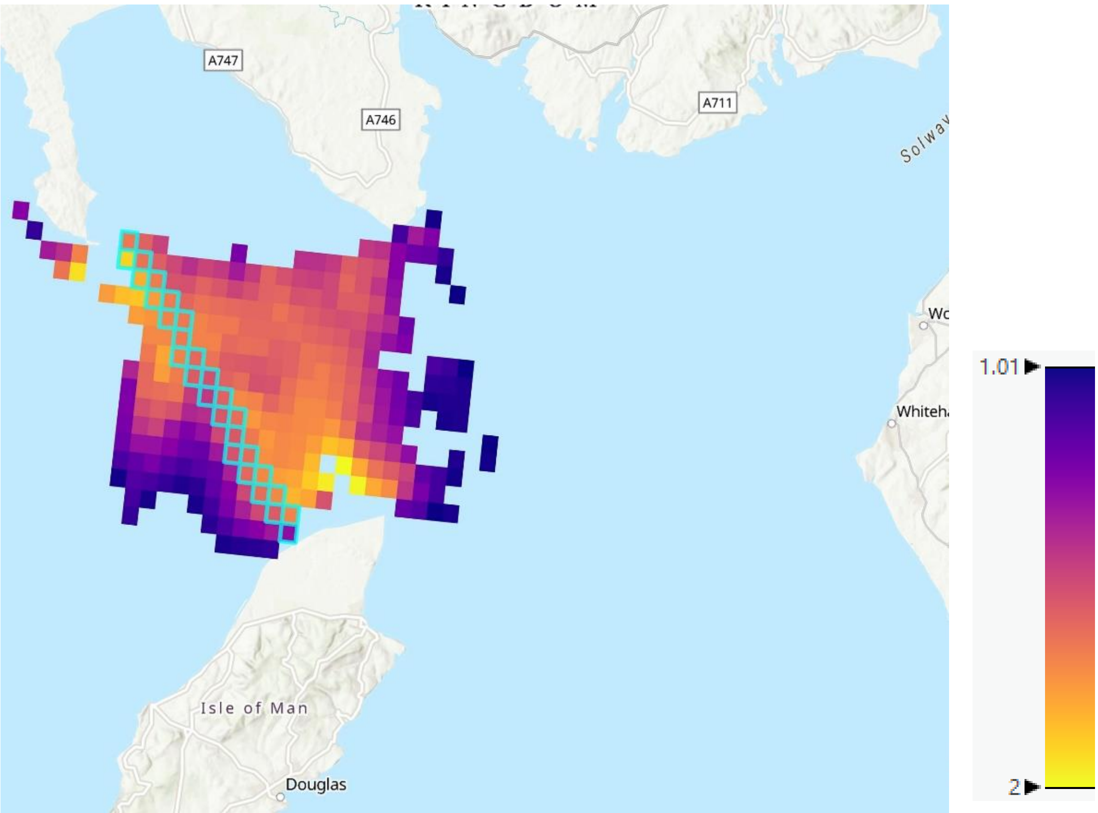

Figure 27 – Line of cells selected across the width of the channel

2. The average depth and spring peak power across the selected cells are calculated

$$d_{Ave} = 36.2\text{m}$$

$$P_{Ave} = 2.5\ kW/m^2$$

3. The width of the channel is measured using a GIS tool

   $b_{channel} = 34{,}620\text{m}$

4. The maximum theoretical power is found using *Equation 16*.

   $P_{Theoretical} = 3.24\ \text{GW}$

5. The maximum theoretical power is multiplied by 20% to find the maximum technically extractable power of the channel.

   $P_{Technical} = 648\ \text{MW}$

6. The maximum technically extractable power is then compared with the technically unconstrained resource.

7. In this case the farm method produced the value of 18GW, which is clearly unachievable when compared to the technically extractable power. Hence, the maximum power that a low speed tidal farm off the coast of the Mull of Galloway could extract is 648 MW. The capacity factor across the channel is then used to find the annual energy yield, in this case 0.156. Hence, the maximum energy yield of a tidal farm off the coast of the Mull of Galloway can be calculated using

$$E = (24 * 365)C_f P_{Technical}$$

Equation 17

8. Therefore the maximum yearly energy yield for a tidal farm off the coast of the Mull of Galloway is 885 GWh/y

It should be noted that this value calculated for the Mull of Galloway energy yield is only a 4% difference to the combined technically extractable energy output, 854 GWh/y, of the Mull of Galloway 'Sites A and B' assessed in Black and Veatch (2005). This verifies the method has been used correctly.

3.3 Selection of suitable sites

The purpose of this study was to identify the potential for low speed tidal power technology to supply electricity to the grid. Therefore, it is useful to identify the best and most viable sites and discuss why they are beneficial.

3.3.1 Aggregated output of phased tidal sites

As discussed in Section 2.3.6, high energy tidal sites in the UK do not have the appropriate phase difference to produce aggregated firm power output. Also mentioned was the need to reduce externality costs to make low speed tidal power more acceptable. Therefore when looking at sites that could be aggregated to make firm power, only areas close to population centres were considered. Hence, the phase difference of sites around Wales, the south, west and east coasts of England and one close to Aberdeen were studied.

As many hydrographic charts and the TotalTide software use Dover as a reference point, this was also done when assessing the phase difference. The time difference between the point of highest speed of the tidal diamond in question and that of Dover's on 22/07/2019 was taken to be the phase difference. An example of this is shown for the Scilly Isles in *Figure 28*.

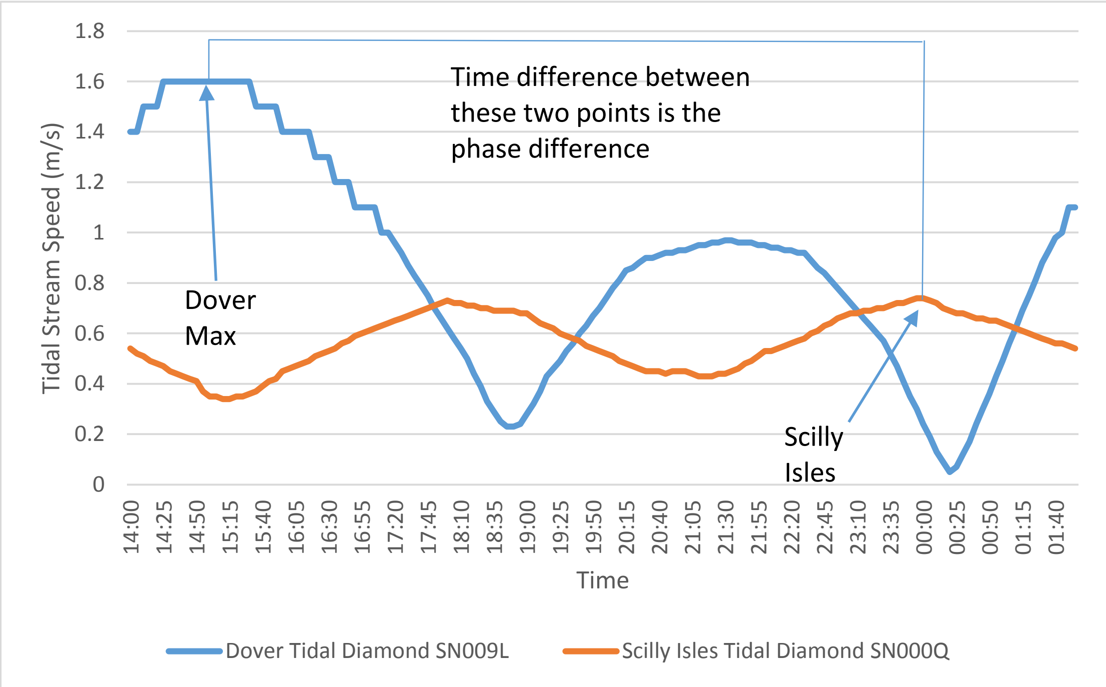

Figure 28 – How the phase difference for each tidal diamond was measured

It must be noted that the phase difference can vary quite drastically between two nearby tidal diamonds due to certain bathymetric conditions causing either the flood or ebb to be the larger tidal speeds.

The phase difference for the selected tidal diamonds were then sorted from smallest to largest in order to inspect how evenly spread they were and further investigate which sites may be suitably out of phase. The spread of tidal diamonds phase difference through a semi diurnal tidal cycle can be seen in *Figure 29*.

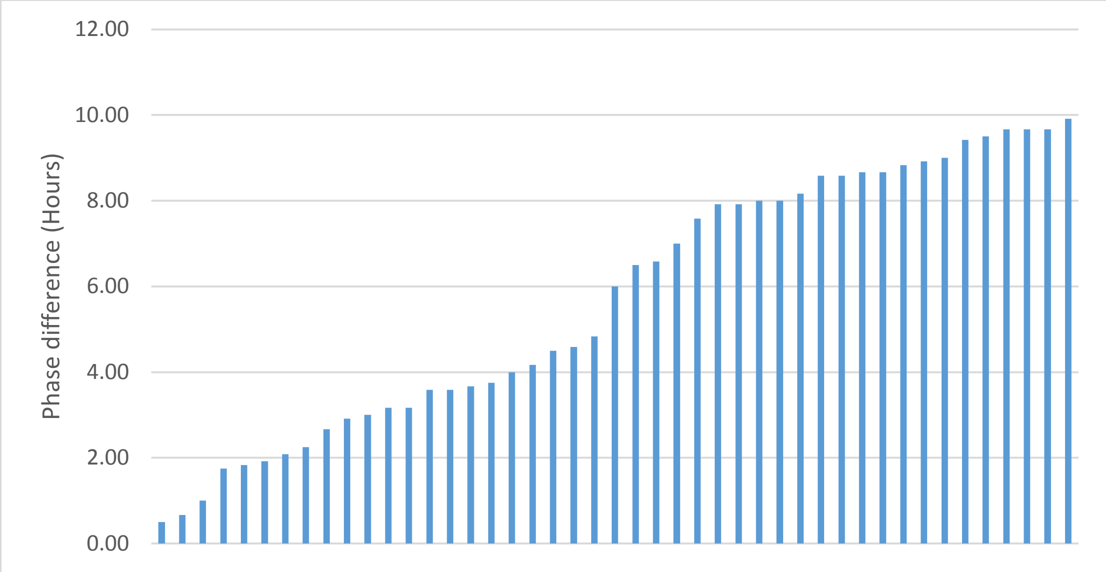

Figure 29 - Distribution of selected tidal diamond phase difference

There are notable gaps between the 5 and 6 hour mark and between 10 and 12 hours.

One flood and ebb tidal cycle is taken to be 12.42 hours (Neill and Hashemi, 2018) and *Equation 18* was used to find the idealised spacing between sites.

$$\emptyset = \frac{12.42}{N_{Sites}}$$

Equation 18

Theoretically, four sites with an even spacing of 3.1 hours between each other would give a relatively smooth aggregated power output. In practice, however, differences between tidal stream speed during flood and ebb tide, require sites to be individually investigated. It must be noted at this point that the individual grid squares associated with each tidal diamond will have slightly different phase difference to its parent tidal diamond. Therefore, closer inspection and site specific modelling could provide more options for suitable phasing. Starting with sites with the smallest phase difference to that of Dover's, adjacent tidal diamonds with as close to 3.1 hours phase difference as possible and grouped together to identify how smooth the aggregated output was.

3.3.2 Most financially viable sites

It is anticipated that it would be useful for tidal stream developers to know which sites in the UK would be the best option for first deployment of low speed tidal stream development.

Identifying the most financially viable single low speed sites around the UK requires taking into account a number of factors, the financial impact of which cannot be estimated accurately in this thesis. For the purpose of this study five key factors were taken into consideration when reviewing sites possible financial viability.

1. Technically extractable power – The energy production that each site is estimated to produce over a year. This was calculated as described in Section 3.2.3, obviously the more energy produced, the more valuable the site is. However, as discussed in section ….. the cost of a turbine required for a 1 ms^{-1}spring peak speed compared to a 2 ms^{-1}spring peak speed could be quite different, so not too much emphasis was placed on this site characteristic

2. Distance from the shore – The distance to the nearest land is listed with each grid square, therefore, sites far from shore are likely to be have high installation costs. Iyer et al. (2013) suggest the cost of undersea cables are £52,000/MW/Km

3. Water depth – The cost of installation can be varied and a number of factors such as bathymetry and cost of structure can affect this. Depth is one that increases the cost of installation proportionally, mostly due to water pressure. Boehme (2006) suggests there is a linear relationship between the cost of installation of offshore wind turbines and the water depth. Boehme (2006) used a correction factor of 1 at 10m and 1.3 at 30m depth.

4. Capacity factor – The capacity factor is the ratio of actual power output to power output if the turbine generated constantly. Therefore it is an important characteristic of a tidal steam site, as it succinctly describes how well the turbine will perform at that site over a year.

5. Distance from population centres – Sites close large population centres were viewed positively as it is likely this would keep externality costs down

It is out with the breadth of this study to try and estimate the cost of installation of low speed tidal turbines and therefore LCoE. However, this study will suggest sites which have the best chance of a lowest possible LCoE.

4. Results

4.1. Distribution of spring peak speeds

The following figure shows a map of the cells spring peak tidal velocity, without any depth restrictions, around the UK coastline.

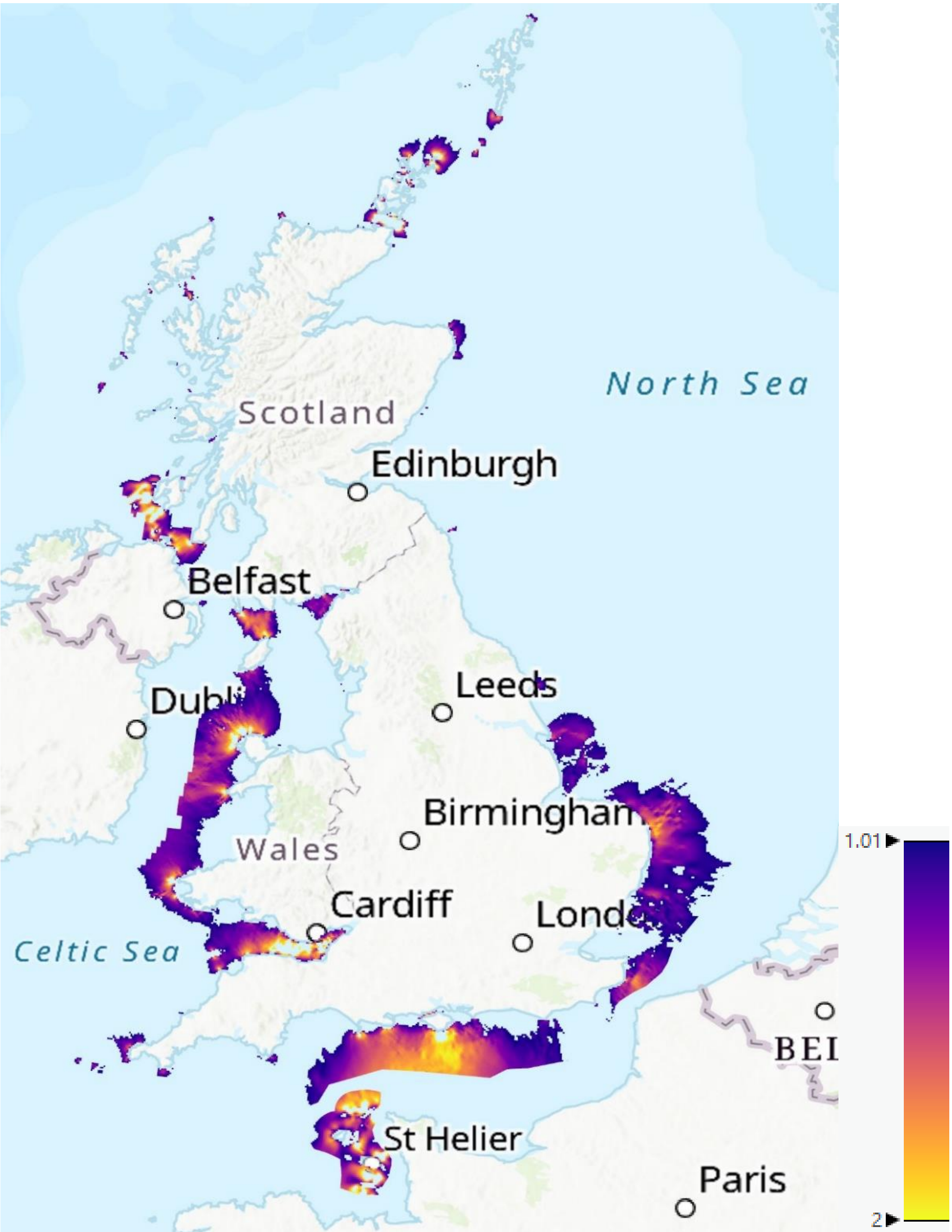

Figure 30 – Map of low speed tidal stream resource in UK territorial waters (ms^{-1})

Figure 31 shows the spring peak tidal stream speeds excluding all cells out with the depth range criterion.

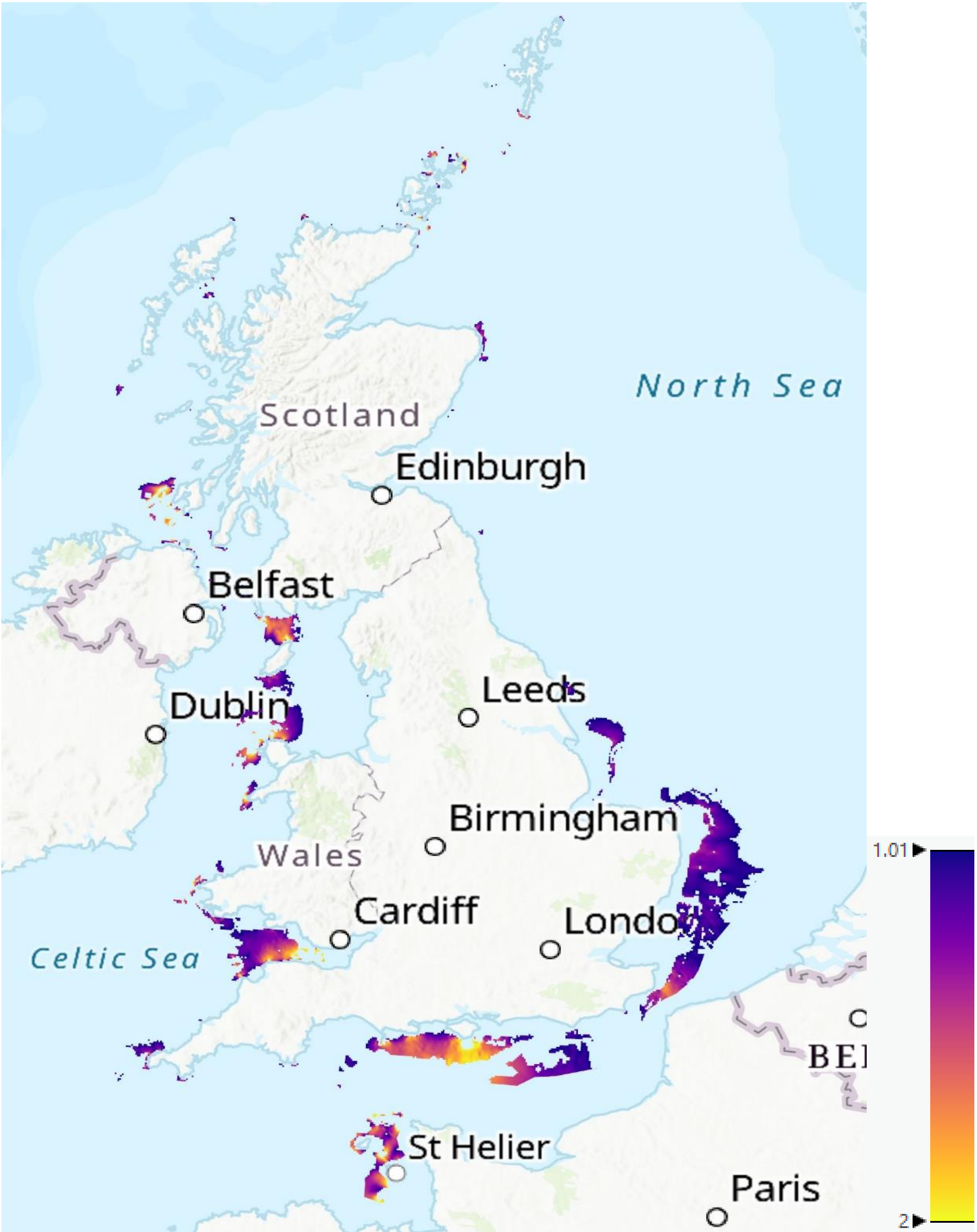

Figure 31 – Map of theoretical resource including depth restrictions (ms^{-1})

High density areas of resource can be seen off the east coast of England, in the Severn Estuary, English Channel and off the west coast of the Isle of Islay. Adding the depth criterion greatly reduces the number of available cells and, hence, the resource available to low speed tidal stream developers. If low speed tidal stream energy is to become a large industry, improvements in installation technology and turbine materials may facilitate deployment at greater depths.

4.1.1 Overall theoretical resource

Using the SIF method discussed, all channels and areas with cells that fit the criteria were assessed for the theoretical resource that could facilitate energy generation. The total maximum theoretical resource found was 55.8 GW of energy, as expected, it falls well within the 200 GW of energy flux that is projected across the North West European Shelf (Blunden and Bahaj. 2007). It must be noted that in cases where cells within the low speed range were sparsely dispersed throughout a channel containing higher speeds, the maximum resource of the channel was calculated using a cross section containing all speeds.

4.2 Technically unconstrained resource

The technically unconstrained resource is the maximum energy that could be extracted from the areas of 1 – 2 ms^{-1}spring peak speed, between the water depths of 25 – 50m, however, not considering how feedback from energy extraction would affect the downstream resource. The distribution of technically unconstrained low speed tidal stream resource capacity around the UK can be seen in *Figure 32*.

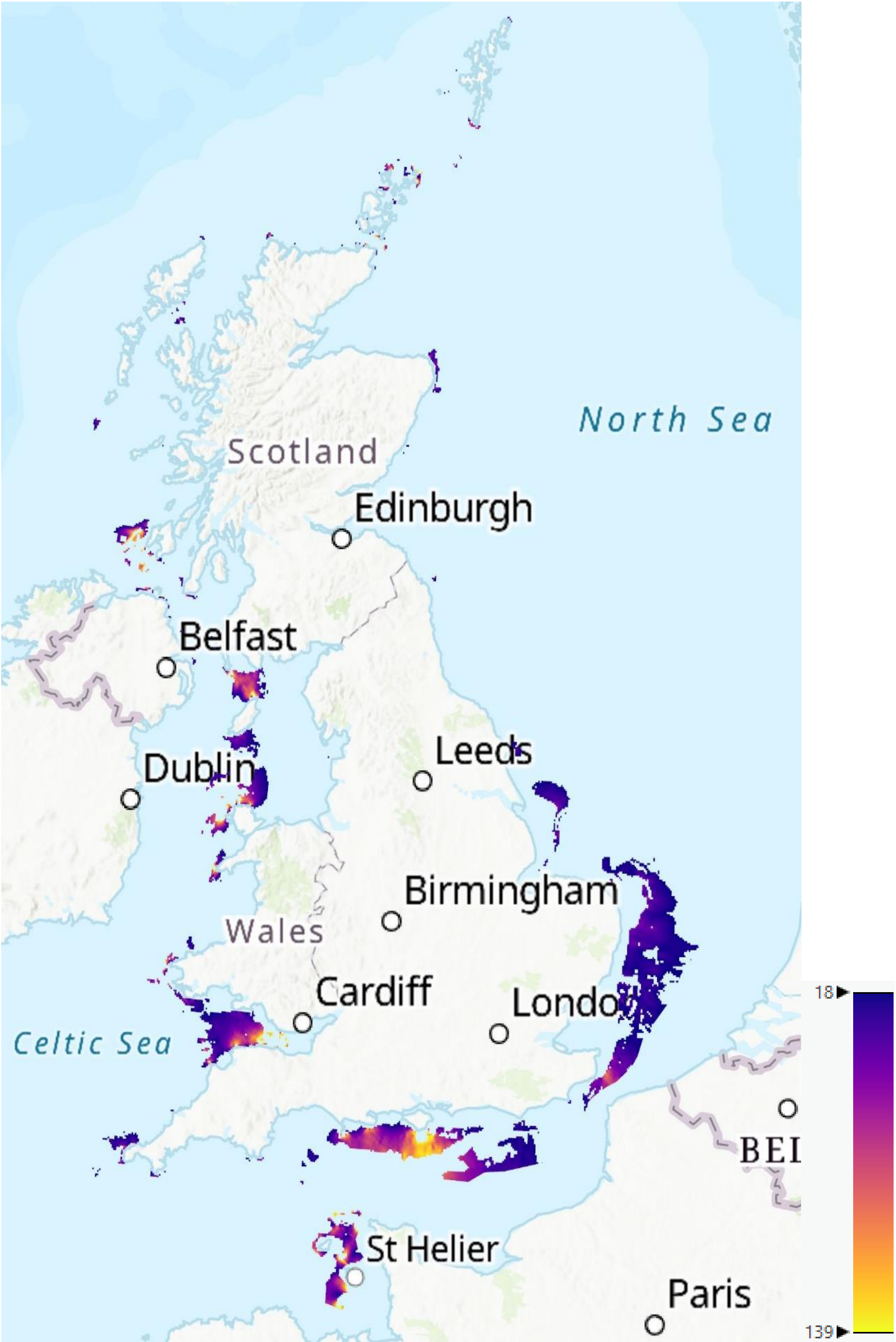

Figure 32 – Distribution of technically unconstrained resource (MW)

The annual energy production calculation involved matching each cell with a parent tidal diamond and then sizing the spring peak speeds and hence time series power output appropriately. Naturally, the cells with peak speeds of close to 2 ms^{-1}will have higher energy yields, however, cells that fall into tidal diamonds with more consistent stream flows can still have relatively high energy yields, even if their spring peak speeds are not the highest. The calculated values only describe the maximum energy that current technology could extract during a year and do not account for feedback. *Figure 33* shows the distribution of the yearly energy yields from the technically unconstrained resource around the UK.

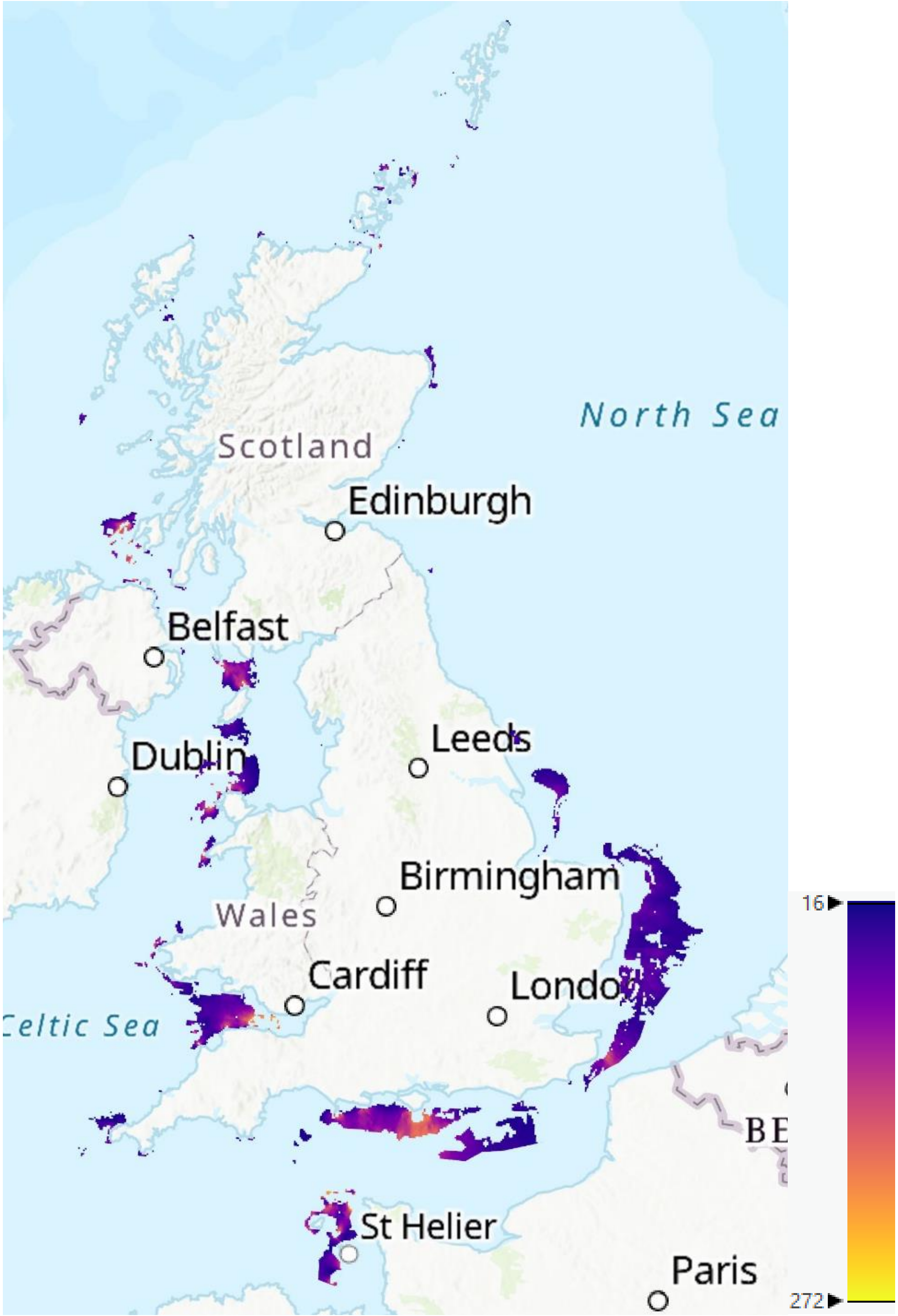

Figure 33 – Annual energy production of unconstrained tidal resource (GWh)

4.3 Capacity Factor

The capacity factor is the ratio of actual power output to power output if a turbine generated full power 24 hours a day, 365 days a year. Therefore, for a developer this is an important characteristic when siting a tidal array. *Figure 34* shows the calculated capacity factor of each cell around the UK. It must be noted that the distinct boundaries are a result of the tidal diamonds in which each cell are associated too, in reality, the capacity factors would not be so rigid.

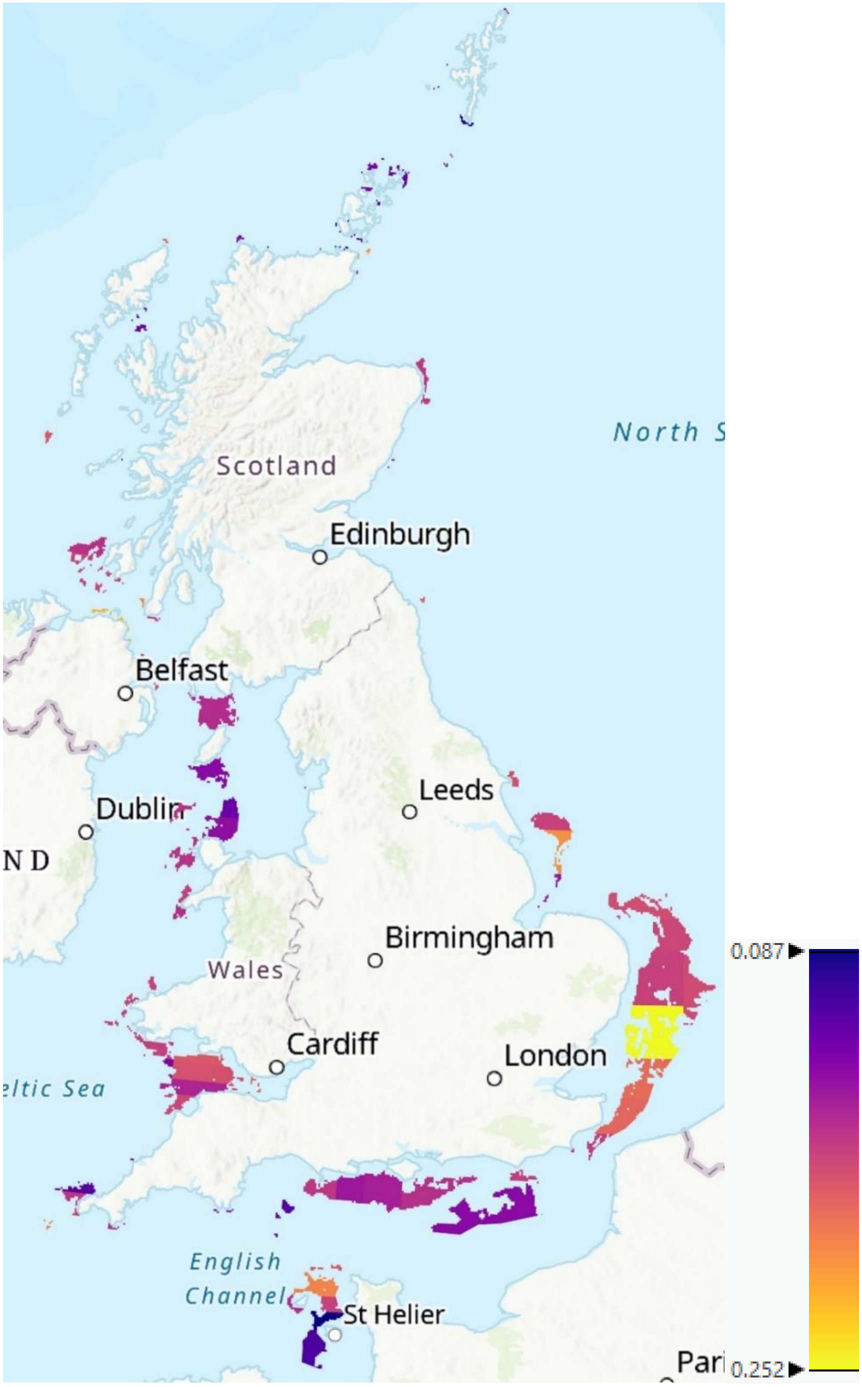

Figure 34 – Average capacity factor

Table 3 shows the minimum, maximum and average capacity factors found by this study.

Maximum	0.252	East Anglia South
Minimum	0.086	Shetland South
Average	0.167	

Table 3 – Minimum, maximum and average capacity factors of low speed sites

The highest capacity factors in the UK were found to be off the coast of East Anglia, an area with a large technically unconstrained resource.

The capacity factors do not reach that of the seven major high energy sites in the UK according to Iyer et al. (2013), although it must be noted that these are calculated with a rated capacity of 70% of spring peak speed. Whilst this technique was considered, it was decided that this thesis should estimate the overall potential energy available to low speed tidal energy developers as it is not yet known if a 70% rated capacity would reduce turbine costs enough to be beneficial. Site specific financial analysis would be required to decide the most suitable capacity rating of energy capture devices.

4.4 Technically extractable resource

The maximum technically extractable energy resource for low speed tidal energy was found using the significant impact factor on every channel with selected cells around the UK. If the technically unconstrained low speed resource was found to be lower than 20% of a channels theoretical resource, then the technically extractable resource was taken as the technically unconstrained power. This was found to only be the case for one site, the Pentland Firth.

The overall technically extractable resource was found to have a maximum capacity of 9.13 GW, which would generate 10.9 TWh/y of electricity. This is equivalent to 3.3% of electricity generation in the UK in 2018 (BEIS, 2019).

Table 4 lists the ten largest sites for low speed tidal energy extraction.

Location	Cells	Theoretical Power (MW)	Technically Extractable (MW)	Capacity Factor	Yearly Energy Yield (GWh)
Pentland Firth	22	11299	1403*	0.141	1733
Isle of Wight	945	3359	672	0.152	895
Mull of Galloway	303	3238	648	0.156	885
Severn Estuary	734	2446	489	0.168	720
Channel Islands North	352	2302	460	0.165	666
Holy Island	98	2178	436	0.160	611
West Islay	167	2153	431	0.162	611
Mid English Channel	672	2073	415	0.138	502
Mid East Anglia	670	1893	379	0.169	561
Channel Islands South	184	1842	368	0.111	358

Table 4 – Ten largest low speed tidal energy sites

**The Pentland Firths technically unconstrained low speed resource, 1403MW, was found to be less than the technically extractable resource of 2260MW.*

It is important to note that most of the ten largest sites are also often listed as sites that are well suited to high energy tidal generation. This is largely because sites of high speed tidal streams are highly likely to have cells of lower speeds within the same channel. If high energy sites are developed downstream from sites of low energy, this would reduce the technically extractable low speed resource. A list of all sites technically extractable power can be found in *Appendix I*.

4.5 Environmental constraints

The environmental constraints imposed by the Marine Conservation Zones of England and Marine Protection Areas of Scotland were added to the GIS layers of the tidal stream data (Jncc.gov.uk, 2019). This can be seen in *Figure 35* below. The areas in green are the Scottish Marine Protection Areas and the areas in purple are the English and Marine Conservation Zones. It must be noted that there are additional zones for Wales and the Isle of Man but the GIS data for these could not be found.

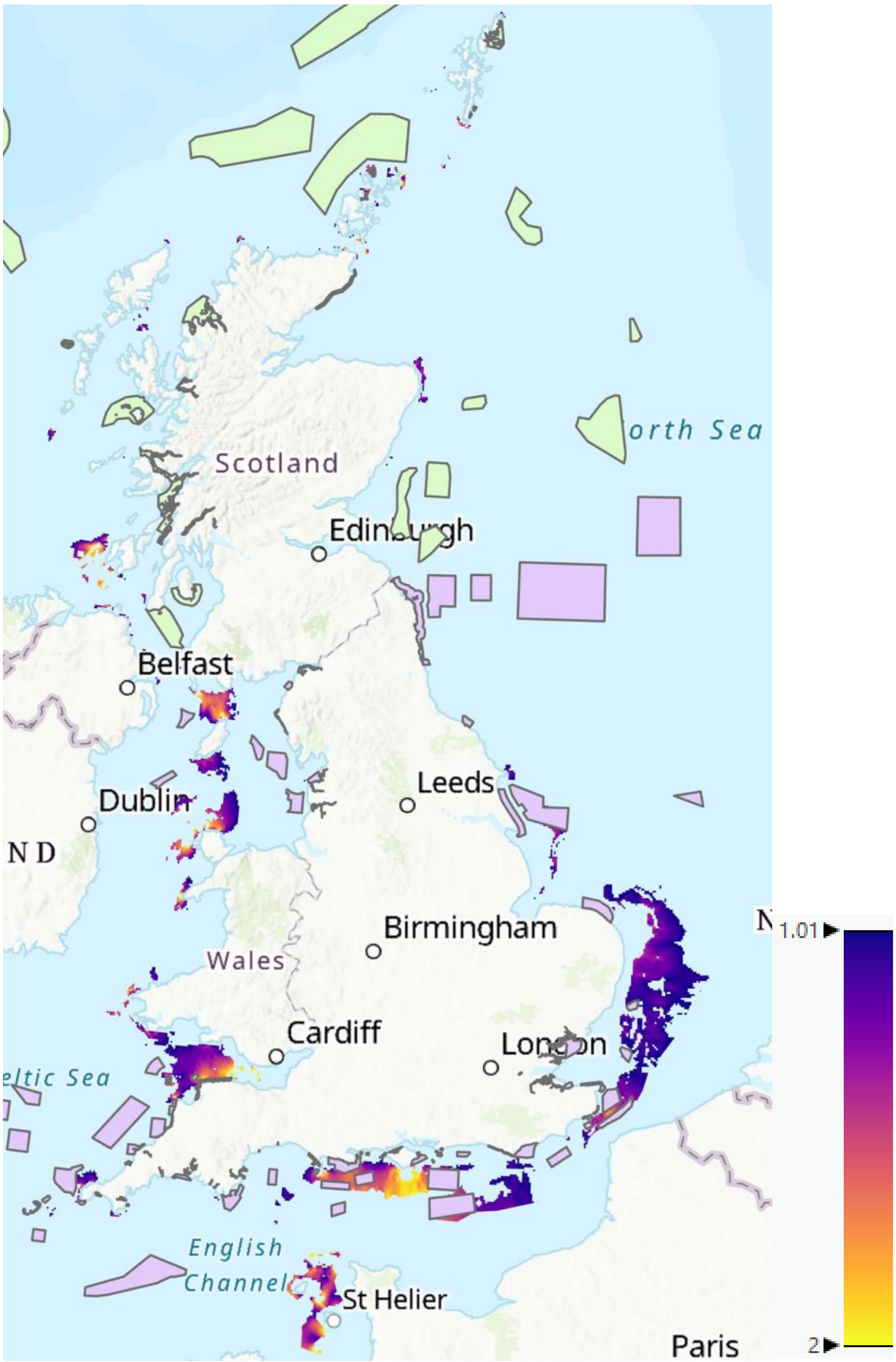

Figure 35 – Marine protection areas projected on low speed resource (ms^{-1})

The analysis found that out of the original 7708 cells studied, 648 cells were discounted due to being in conflict with MCZs and MPAs. This relates to a reduction of 8.4% of identified cells and 2100 km^2 of sea space.

It must be noted that if a cell was partially in conflict with the environmental constraints, then it was not discounted.

Most major sites were not affected by the environmental constraints because the reduction in technically unconstrained power did not surpass the technically extractable power. There were a few small sites, however, that were not further considered as potential developments because the environmental constraints were fully in conflict with the site. These can be seen below; the resultant value for total technically extractable power was reduced to 9.0 GW.

Location	Cells	Technically Extractable Power (MW)	Yearly Energy Yield (GWh)
Farne Islands	6	37	60
Mull of Kintyre	9	71	104
Wick	2	13	16
Trevose	2	7	8
Total	19	128	187

Table 5 – Sites eliminated due to environment constraints

4.6 Suitable sites for deployment

A number of factors affect sites suitability for tidal array deployment. Considered in this study are technically extractable power, capacity factor, distance from shore, depth and distance to population centres. Hence, this next section will not just focus on sites with the biggest potential energy output, but sites that would be most financially suitable for deployment.

4.6.1 Rathlin Island

Situated off the north coast of Northern Ireland, tidal stream peak spring speeds of up to 2 $ms^{-1}$are prevalent between Rathlin Island and mainland Ireland.

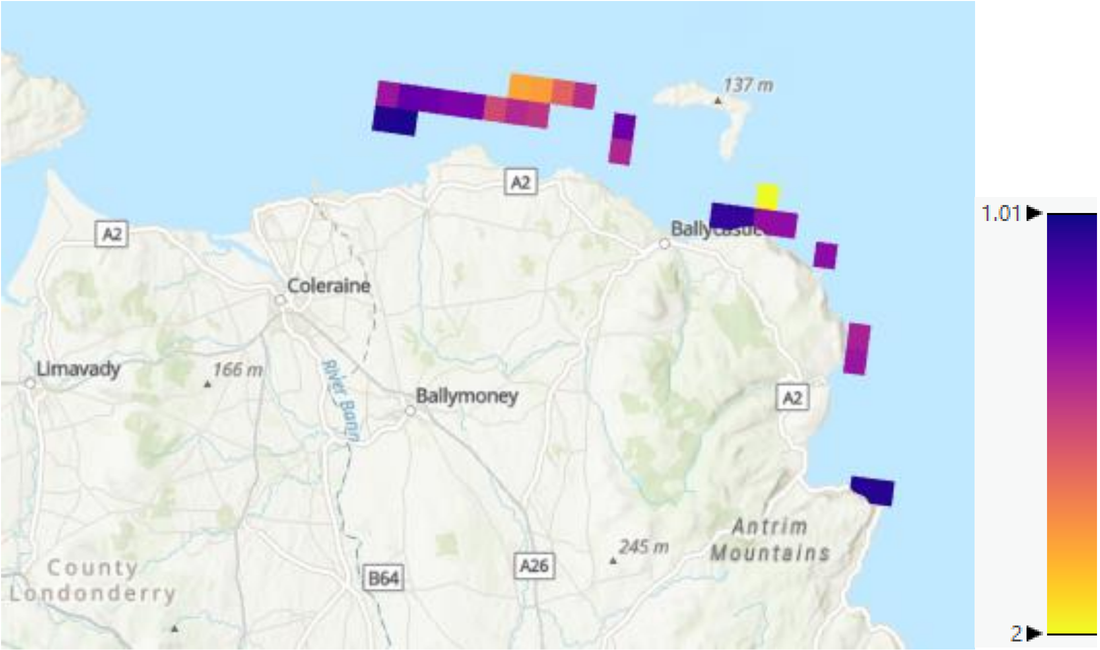

Figure 36 – Map showing the tidal resource off the coast of Rathlin Island (ms^{-1})

The cells identified by the low speed criteria are a maximum distance of 6km from the coast and some of the cells have a negligible distance to the coast. The sites enjoys a high capacity factor, second highest of all the sites, making it an attractive option for developers. These factors, along with an average depth of 36m are likely to produce one of the lowest LCoEs of any site identified. With a large population centre nearby, Belfast, a development would not incur large transmission costs. The maximum technically extractable capacity of the site is 159 MW and could produce 311.2 GWh/y with a capacity factor of 22.4%.

4.6.2 East Anglia

Off the coast of East Anglia lies large swathes of cells that fall within the low speed criteria. The area shown below has an estimated technically extractable capacity of just over 1 GW and some areas with high capacity factors. The region is also relatively close to London and surrounding high density areas making it favourable from a grid transmission point of view. It must be noted that most of this area has peak spring speeds closer to 1 ms^{-1}, therefore the design of turbines cheap enough to make the site financially viable is vital. The figure also shows the overlap of environmental constraints in the area.

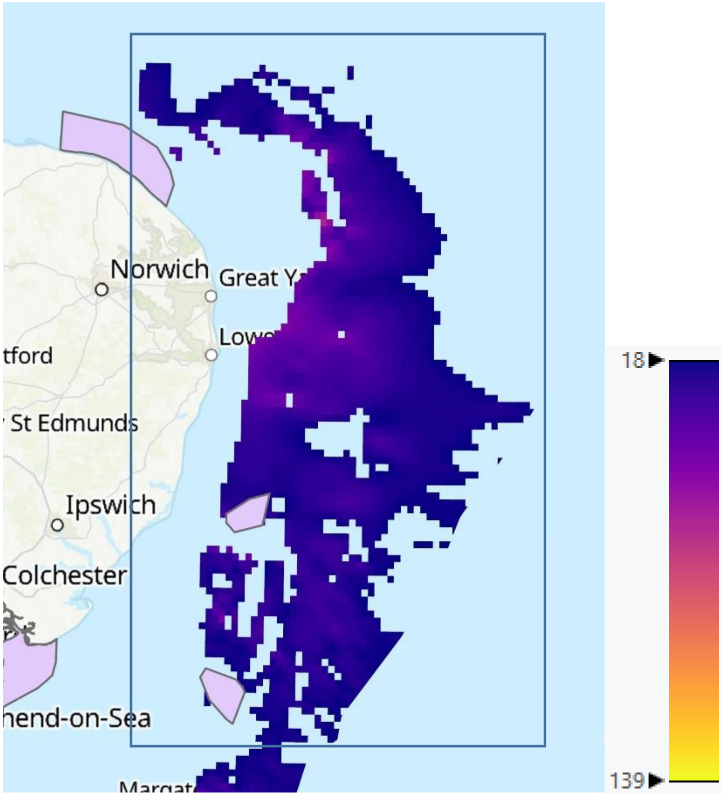

Figure 37 – Area off the east coast of East Anglia

The size of the potential site means that if developed it could become a significant part of the UKs electricity generation mix. Deployment would lead to high learning rates of low speed tidal energy and could reduce costs greatly due to volume production. *Table 6* shows the area split into four parts.

Location	Cells	Technically Extractable (MW)	Capacity Factor	Yearly Energy Yield (GWh)
Thames Estuary	430	200	0.233	408.2
South East Anglia	551	265	0.213	494.5
East Anglia North	540	169	0.173	256.1
Mid East Anglia	670	379	0.169	561.1
Total	2191	1013	0.197	1720

Table 6 – Breakdown of the East Anglia site

One obstacle that large scale deployment off the coast of East Anglia would have to overcome is the large distance to shore. Some cells in the area are 82km from the UK coast, therefore requiring a large investment in electricity connection. It is noted, however, that there is a large overlap between the area identified in *Figure 37* and a large scale deployment of offshore wind turbines. Whilst there is potential for conflict, there is also potential for the sharing of grid connection infrastructure and even support structures as discussed by Lande-Sudall et al. (2019). *Figure 38* shows the areas that overlap (Thecrownestate.co.uk, 2019).

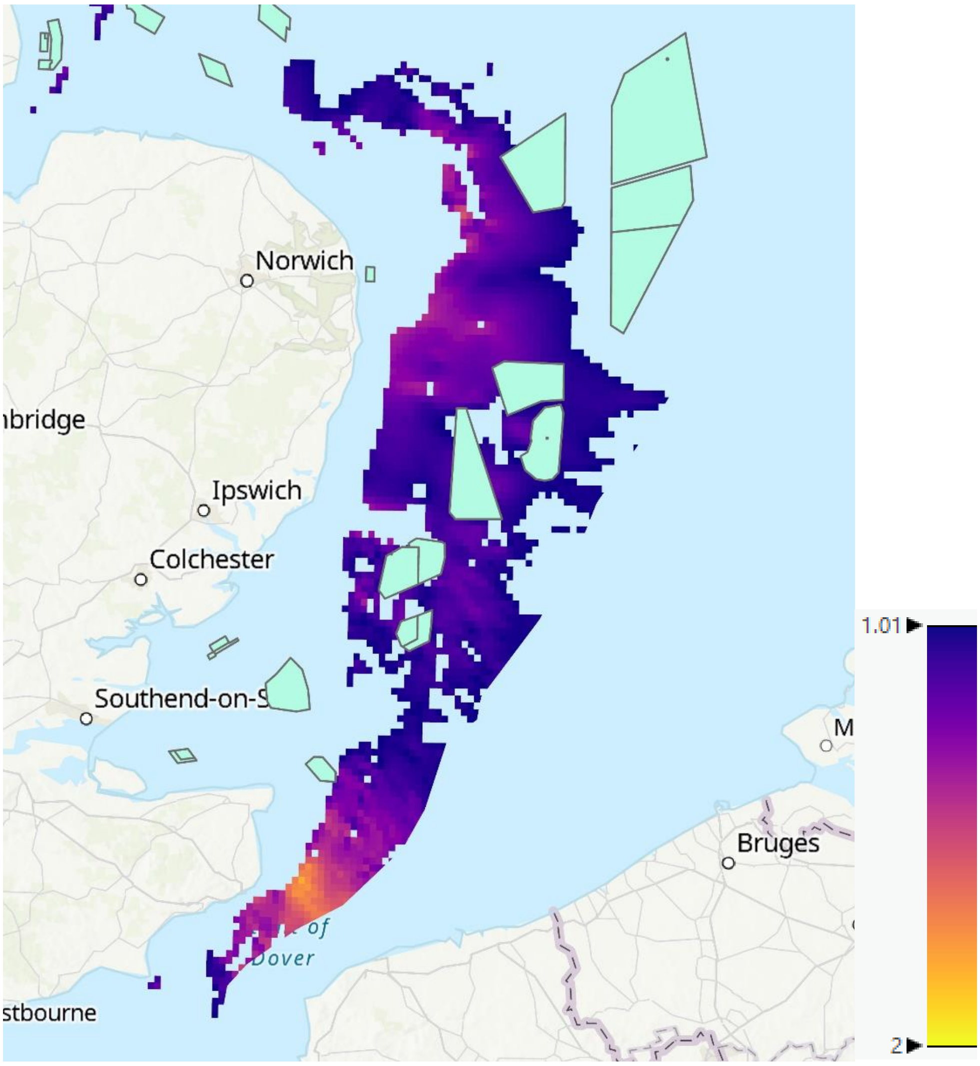

Figure 38 – Overlap of offshore wind farm areas off the coast of East Anglia

4.6.3 Machrihanish Bay

Machrihanish Bay is situated off the west coast of Kintyre and has potential for a 25 MW capacity tidal array at a capacity factor of 20.7%. The overall technically extractable capacity is not large, however, the high capacity factor and short distance from shore make it a suitable location for deployment and has potential for a low LCoE. It must be noted that transmission capacities on the Kintyre peninsula may constrain the development. The site can be seen in *Figure 39*.

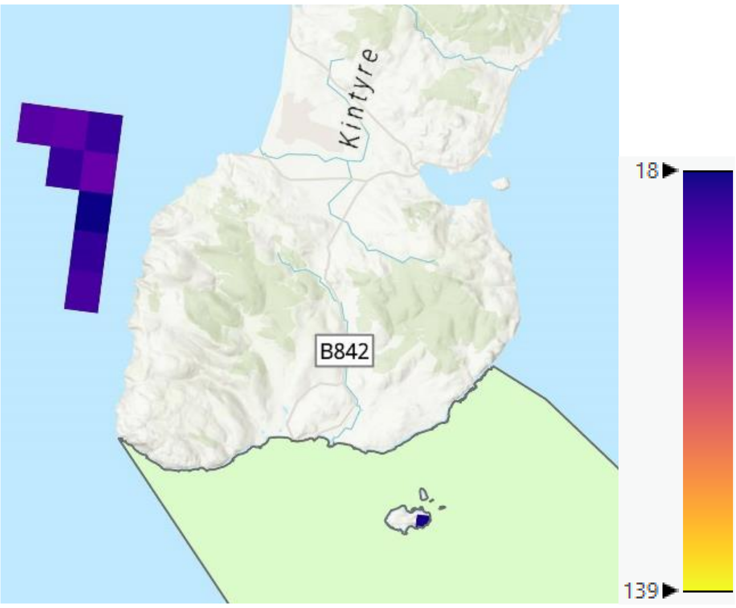

Figure 39 – Technically unconstrained power at the Machrihanish Bay site (MW)

4.6.4 Dover

The area off the coast of Dover, directly south of the East Anglia region discussed in Section 4.6.2, has many of the same favourable characteristics as its neighbour. It has cells with speeds of 1.81 $ms^{-1}$and a large potential site capacity, 255 MW. Due to its location, however, it may be in great conflict with the shipping industry that is so prevalent in that region. *Figure 40* shows the max spring speed distribution of the Dover region.

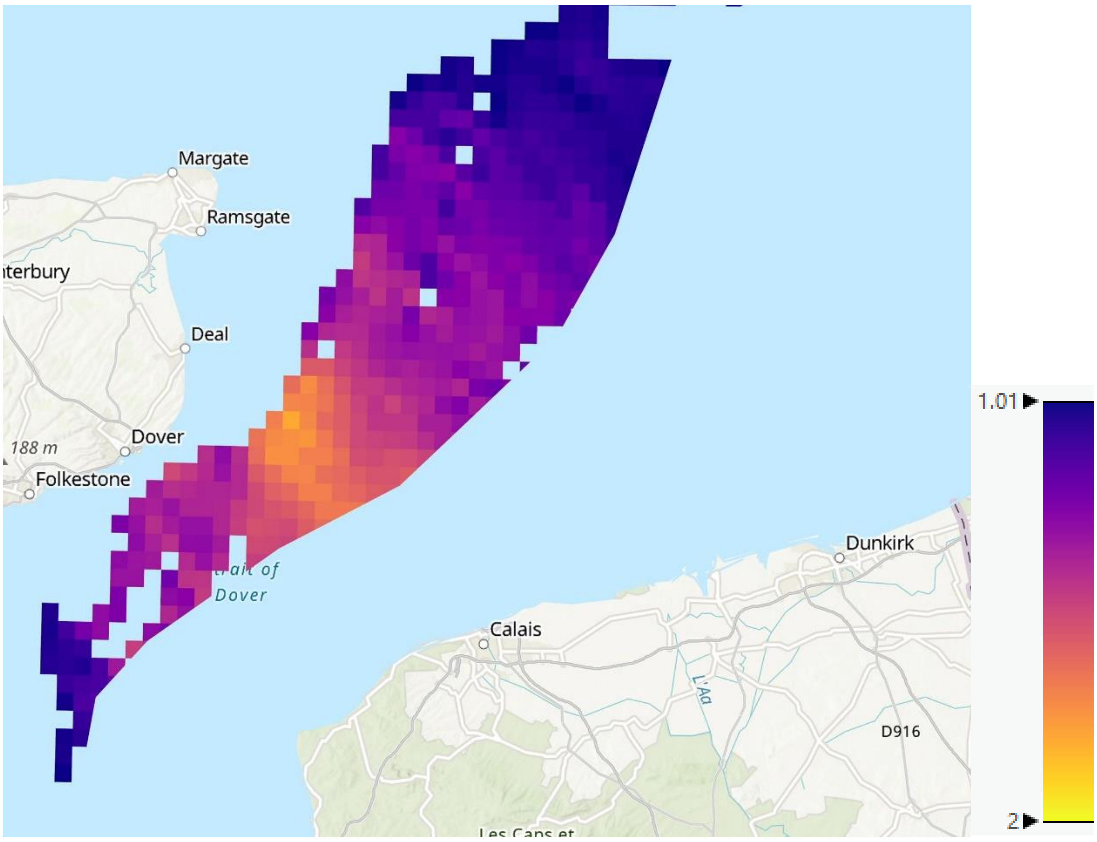

Figure 40 – Max spring peak speeds of the Dover region (ms^{-1})

4.6.5 Island communities

Rathlin Island has already been identified as a suitable place to site low speed tidal turbines, but an array there has potential to export a large amount of energy to mainland population centres.

The Isle of Coll has a single cell located 1.8km off its east coast and has a maximum technically extractable power of 9 MW. Whilst this is a relatively small amount, Coll only has a population of around 150 people (Visitcoll.co.uk, 2019). The site can be seen in *Figure 41*.

Figure 41 – Isle of Coll's low speed tidal site

The average person in the UK consumes around 5MWh of electricity per year (Databank.worldbank.org, 2019), therefore an estimate of the yearly electricity demand for the Isle of Coll is 750 MWh. This is well below the maximum 10.3 GWh that a tidal array could generate in a year for the island.

4.7 Firm power

All sites reasonably close to population centres, discussed in Section 3.3.1, were considered for aggregation to generate firm power. It was also decided to add in the Pentland Firth site, operating at a maximum 400 MW in the assumption that the Meygen site will be operational in the near future. The resultant time series data for a day at spring peak tides can be seen in *Figure 42*.

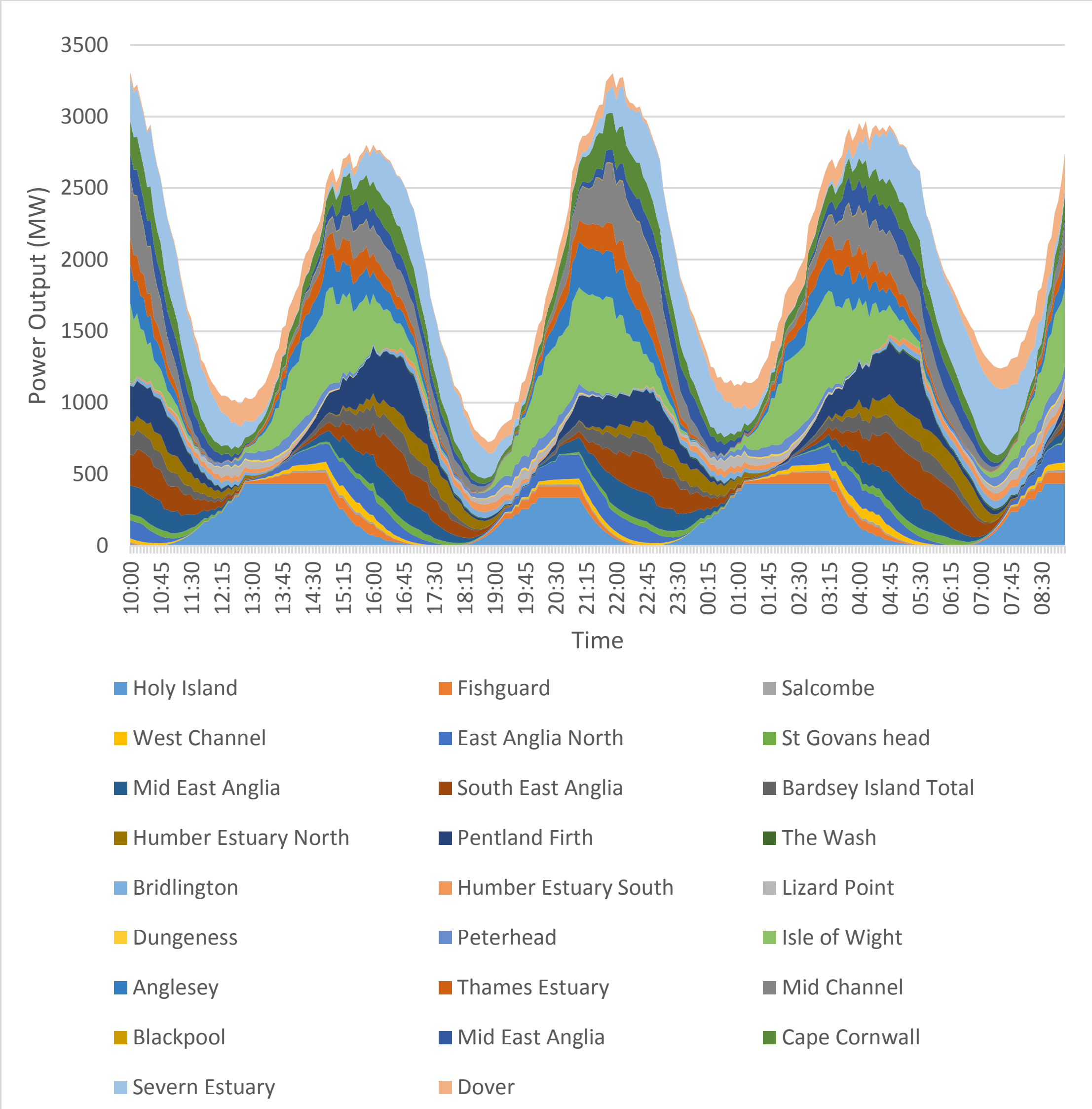

Figure 42 – Aggregated technically extractable power output of sites close to population centres

The aggregation gives a degree of firm power at spring tides, 710 MW, but it is noted that there are a few key sites that have a suitable phase difference. By removing sites that are largely in phase, the most important areas to site tidal arrays can be identified.

Figure 43 shows the sites that are left and the aggregated power output of them.

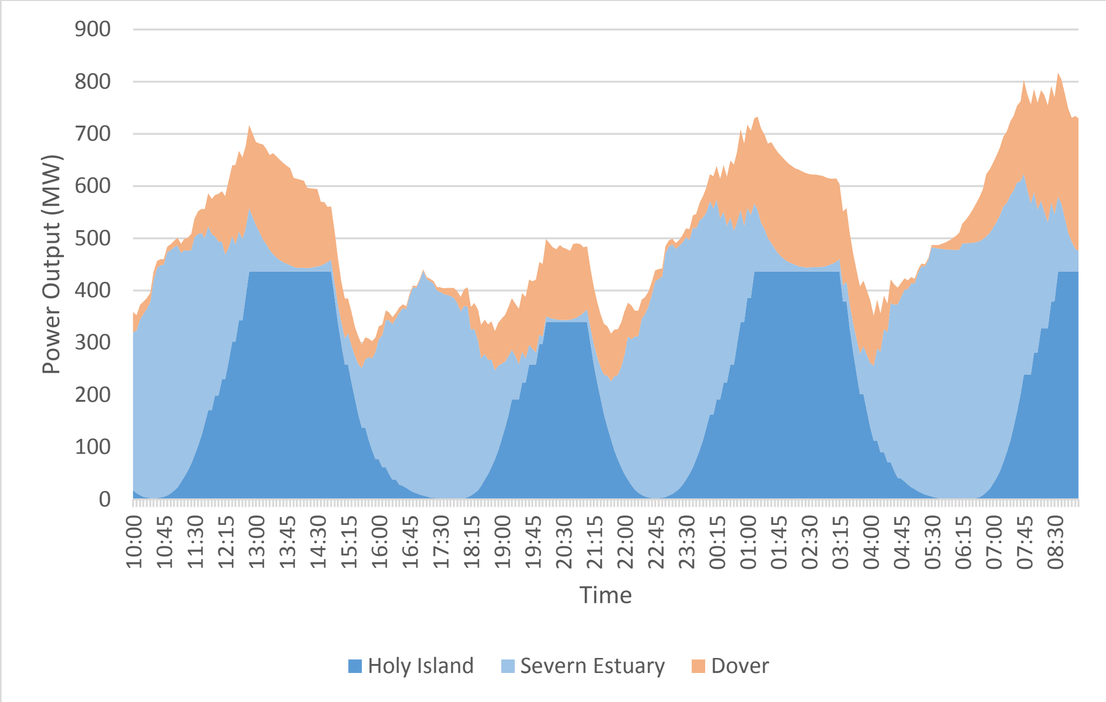

Figure 43 – Aggregated power output of three out of phase sites

The output gives a good degree of firm power at spring peak tide, 300 MW. The sum of the three sites is 1180 MW and this value could be reduced if the rated capacity of turbines was altered to smooth out overall aggregated fluctuations in supply.

5 Discussion

The results give a good estimate of the overall resource for low speed tidal generation in the UK. The findings show that there is a large resource available for low speed tidal developers, however, the potential for large scale extraction of this energy requires a lot of research into reducing the cost of turbines by choosing cheaper materials and manufacturing methods. Deployment of low speed arrays is dependent on accurate financial analysis and testing of cheaper turbines at the sites identified in this study. Whilst this thesis gives a good overview of the total resource in the UK and highlights suitable areas; deployment of low speed turbines would of course require site specific assessment of tidal flows.

The study has identified suitable sites, not just dependent on overall output, but also suggested sites that would be suitable for deployment due to other factors such as capacity factor and distance from shore. The distribution of resource shows there is potential for large scale tidal arrays off the coast of East Anglia, Wales and the Mull of Galloway, in the English Channel, the Channel Islands and the Orkney Isles. The study has found that proposed areas for marine protection in the UK only reduce the extractable resource slightly. The overall findings of the resource assessment are very positive for the future of low speed tidal stream energy and the aggregation of out of phase sites make the technology favourable if installation costs can be reduced enough for it to be viable.

The method to calculate the potential resource used primary tidal stream speed data from the Marine Renewables Atlas. The atlas data is a good way to observe the distribution of resource around the UK and therefore identify suitable sites, however, it requires manipulation to estimate the overall potentially extractable resource. It must also be noted that the cells in which each data point is stored and parameters averaged over have a relatively large resolution of 1.8km. Lewis et al. (2015) found that resource estimation is sensitive to coarse spatial resolution, especially at low speeds.

Time series data was gathered from the UKHO software package, TotalTide, which predicts tidal stream speeds and tidal ranges at locations of tidal diamonds. The software is useful and predictions it makes are based on finely tuned tidal models and recorded stream data. It is important to note that tidal diamonds are not always located nearby the marine renewables atlas cells in which this thesis has studied, resulting in a small error in the phase and time series of some sites. The time series data of the TotalTide software also creates a rounding uncertainty because it displays only one decimal place above speeds of 1 ms^{-1}. However, this is unlikely to significantly affect the results.

The SIF method used was important to incorporate the maximum extractable energy from a system, without having adverse effects on tidal flows down stream of energy capture devices. Simply using the technically unconstrained method would result in a gross overestimate of the resource and be useful in identifying sites of large scale deployment. The SIF method was updated in Black and Veatch (2011) but still gives a good approximation of the tidal resource, this is confirmed by the SIF method used in Black and Veatch (2005) falling well within the 2011 study limits. Future work should be done to improve the estimation of low speed tidal resource, possibly using the method set out in Black and Veatch (2011).

6 Conclusion

The main aim of this thesis was to assess the potential resource of low speed tidal stream generation in the UK. The analysis estimated that low speed sites around the UK have the potential for a capacity of 9.13 GW of tidal power generation producing 10.9 TWh/y of electricity. Proposed environmental constraints imposed by government regulations only reduce this to 9 GW. The results show that low speed tidal energy generation has the potential to produce a significant part of the UKs electricity generation mix, 3.3%. Whilst not analysed in this study, it is clear that total resource could be greatly increased if turbines were to be deployed at greater water depths in the future.

The analysis has shown that low speed sites are much better situated with areas of population when compared with high energy tidal stream sites. The results showed large potential for deployment off the west, east and south coasts of England and Wales. It is important to note that several potential sites in this study are in close proximity to sites already identified for high energy tidal stream generation; this must be taken to into account when siting low speed tidal arrays in future.

The site with the highest capacity factor identified was a large area off the coast of East Anglia, large scale deployment would be suitable there, however, long distances for electrical connections to shore will increase the overall cost of a project there.

Rathlin Island off the coast of Northern Ireland, is one of the most suitable sites for deployment due to a high capacity factor and being close to shore. This would be a sensible choice for first deployment of low speed tidal power technology.

There are a few sites that would be suitable for small scale generation to supply island communities, low speed tidal power could provide a substantial proportion of Coll, Skye and Lewis's electricity demand. Remote communities like Foula, Shetland could benefit from the technology, but it is noted that it is unknown if it will ever be cost effective for such a place.

It was found that three key sites, Holy Island, Severn Estuary and Dover could generate 300 MW of firm power at spring tides. This work has proved suggestions that low speed tidal resource would have sufficient phase difference to produce firm power.

7 Future work

Still in the early stages of development, little is known about the potential for low speed tidal energy generation. This study has provided a good estimation of the UKs extractable resource and detailed suitable sites for first deployment.

Work must be done in estimating the cost of tidal turbines suitable for low speed generation. Structural modelling of a tidal turbine working in low speeds should be conducted and the most suitable turbine materials identified. The cost of manufacturing such a turbine should be estimated and work could be done on how volume production would affect costs. A strong financial analysis should be conducted to estimate the potential LCoE of a site such as Rathlin Island.

Methods for estimating extractable tidal energy are still evolving and improving on this thesis by using the Black and Veatch (2011) method may give a greater degree of accuracy. Analytical modelling of the whole UK tidal system should be done so that the effect on channel flows caused by tidal arrays can be scrutinised and any interference with the tidal environment is kept to a minimum.

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Appendix I

Location	No. of Cells	Technically Unconstrained(MW)	Theoretical Power (MW)	Technically Extractable Power (MW)	Capacity Factor	Yearly Energy Yield (GWh)	Average Depth (m)	Min Distance (Km)	Max Distance (Km)	Max speed (ms^{-1})
Fladda Chuain	19	586	268	54	0.126	59.6	33	5	11	1.54
Shiant Islands	7	228	183	37	0.121	39.2	32	1	6	1.47
Butt of Lewis	5	115	80	16	0.186	26.1	33	2	4	1.19
Cape Wrath	10	412	262	52	0.129	58.8	42	2	5	1.71
Durness	1	18	40	8	0.104	7.3	41	2	2	1.02
Thurso	1	18	43	9	0.145	22.9	46	1	1	1.01
Pentland Firth	22	1403	11299	2260	0.141	1732.9	39	0	9	1.97
Graemsay	1	32	105	21	0.104	29.2	28	0	0	1.22
Rousay	12	600	226	45	0.135	53.5	32	1	6	1.85
Shapinsay	5	132	112	22	0.118	23.2	32	2	5	1.31
Papa Westray	22	1348	598	120	0.131	137.2	44	0	17	1.98
North Ronaldsay	40	2230	704	141	0.120	148.0	37	1	12	2
Fair Isle	6	253	215	43	0.128	48.2	41	0	2	1.61
Shetland South	16	924	372	74	0.086	56.0	40	0	4	1.7
Foula	2	38	76	15	0.117	15.6	38	4	7	1.05
Papa Stour	1	21	50	10	0.117	10.2	26	0	0	1.07

Skaw	4	126	120	24	0.121	25.4	42	0	2	1.33
John o Groats	3	133	114	23	0.213	42.5	40	1	1	1.52
Wick	2	57	64	13	0.139	15.8	43	2	2	1.2
Peterhead North	34	1169	393	79	0.162	112.1	40	1	10	1.56
Peterhead	33	957	425	85	0.162	120.6	42	1	9	1.37
Montrose	3	67	72	14	0.140	17.2	28	2	3	1.13
Farne Islands	6	152	186	37	0.184	59.6	37	1	3	1.25
Bridlington	29	673	264	53	0.176	81.7	40	1	7	1.31
Humber Estuary North	241	6241	781	156	0.181	247.3	32	13	47	1.39
Humber Estuary South	36	1052	266	53	0.181	84.0	32	20	29	1.39
The Wash	7	180	60	12	0.143	15.0	26	8	12	1.22
East Anglia North	540	12404	846	169	0.173	256.1	31	11	61	1.54
Mid East Anglia	670	18437	1893	379	0.169	561.1	34	8	82	1.42
South East Anglia	551	12280	1323	265	0.213	494.5	36	11	75	1.31
Thames Estuary	430	9533	1000	200	0.233	408.2	37	19	69	1.36
Dover	477	18954	1273	255	0.186	415.5	35	2	47	1.81
Dungeness	3	76	71	14	0.155	19.0	28	1	2	1.19
Mid Channel	672	24327	2073	415	0.138	501.7	45	3	69	1.73
Isle of Wight	944	67708	3359	672	0.152	894.8	37	1	33	2

West Channel	40	875	350	70	0.117	71.7	45	34	51	1.22
Channel Islands North	352	19984	2302	460	0.165	665.9	38	5	20	2
Channel Islands South	184	11026	1842	368	0.111	358.2	39	5	35	2
Salcombe	7	225	92	18	0.128	20.2	39	1	3	1.46
Lizard Point	10	320	341	68	0.153	91.1	38	0	3	1.4
Cape Cornwall	119	3304	1348	270	0.140	331.1	41	0	25	1.63
Trevose	2	42	34	7	0.130	8.0	28	0	1	1.12
Severn Estuary	734	34400	2446	489	0.168	719.7	40	0	23	2
St Govans Head	79	2200	286	57	0.166	82.9	40	0	15	1.6
St Annes Head	17	604	220	44	0.166	64.0	40	0	6	1.71
Grassholm Island	12	659	778	156	0.166	226.8	45	10	22	1.68
Ramsey Island	30	1871	777	155	0.168	228.1	44	0	8	1.94
Fishguard	22	516	396	79	0.168	116.3	46	2	13	1.29
Bardsey Island	66	3053	696	139	0.161	196.0	27	0	8	1.96
Holy Island	98	6358	2178	436	0.160	611.1	44	0	28	2
North Anglesey	265	10625	1314	263	0.134	308.7	45	0	41	1.98
Outer Anglesey	43	1555	288	58	0.160	81.3	48	11	36	1.45
Blackpool North	1	21	33	7	0.149	8.5	29	4	4	1.07

South Isle of Man	166	4877	714	143	0.136	170.1	42	0	27	1.61
Mull of Galloway	303	1821 7	3238	648	0.156	885.0	38	0	18	2
Copeland Island	6	149	121	24	0.178	37.7	35	2	6	1.2
Rhins of Galloway	2	39	48	10	0.137	11.5	47	2	2	1.06
Larne	2	56	147	29	0.153	39.4	47	6	7	1.28
Rathlin Island	29	1333	793	159	0.224	311.2	36	0	6	2
Mull of Kintyre	9	324	353	71	0.168	103.9	40	1	4	1.64
Machriha-nish Bay	8	248	125	25	0.207	45.3	38	1	6	1.33
Inner South Islay	19	1221	442	88	0.171	132.4	40	0	11	1.99
Outer South Islay	41	3534	1387	277	0.170	413.1	45	13	267	2
West Islay	167	9422	2153	431	0.162	611.1	37	2	35	2
Coll	1	21	44	9	0.133	10.3	40	2	2	1.06
Barra Head	19	569	334	67	0.180	105.3	30	22	33	1.39
Total	7708		54.84	9.13		10.9				
			GW	GW		TWh/ y				