Department of Mechanical and Aerospace Engineering

Integration of Pump Hydro Storage with a Tidal Stream Array to Achieve a Base Load

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Copyright Declaration

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Signed: Date: 6th September 2014

Abstract

This thesis examines the feasibility of using pump hydro storage (PHS) as a storage solution to renewable energy generation. The renewable energy technology investigated is tidal stream energy. A tidal stream energy system proposed for construction in the Pentland Firth was examined. As tidal stream generators are located in the coast surrounded by seawater, the thesis focuses on possible sites to deploy a seawater PHS system; this eliminates the need for a lower reservoir and only requires the construction of an upper reservoir thus easing the deployment of PHS systems. Two sites were identified and studied. A tool was developed using excel that can be used to gain the theoretical available energy in a reservoir with a known volume. The tool can also be used to find theoretical pump turbine outputs.

Site 1 investigated was a PHS system on Dunnet Head. Using the sizing tool developed, the potential maximum energy able to be stored by the system was identified; 164MWh. Site 2 was located in Thurso, where the theoretical maximum capacity of the PHS system in site 2 was found to be 870MWh. Both sites are located on the Scottish mainland close to the Pentland Firth.

There is a tidal stream energy project proposed for the Pentland Firth called MeyGen. A modeling of the available power from MeyGen was investigated. The idea is to use a PHS to allow for a base load profile to be achieved from integrating the tidal energy array with a PHS. It was found that a PHS could be used to allow a tidal array to produce a base load.

Acknowledgements

I would like to thank my supervisor, Dr. Andry Grant for all the advice and guidance throughout the period of completing this thesis. It was great working with Dr. Andy.

I would also like to thank my family members, mom, dad, abang and kakak for all their support throughout my study years being abroad from home and my beloved fiancée for the calm she has brought into my life. Not forgetting my beloved cats that accompanied me during my study period.

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Introduction

The drive to find new methods to meet the ever-increasing demand of electricity has led to the development of the renewable energy sector. Many technologies have been deployed such as wind, solar, wave and tidal generation. The drive to generate energy by renewable means is not just to meet the energy demand; it is also to ensure the reduction of greenhouse gasses in the environment. The United Kingdom has targets to meet 15% of its energy demand by renewable sources by 2020.

In Scotland, the target to achieve 100% generation of electricity from renewable technologies has been set for the year 2020. The Scottish government is committed to meeting this target thus there is a large-scale deployment of renewable technologies happening around Scotland. Due to the geographical nature of Scotland, the resources that are abundant are wind, wave and tidal energy. The potential energy that can be extracted from these resources in Scotland are amongst one of the highest in the world.

Although Scotland has a lot of potential for renewable energy, these renewable energy technologies are intermittent. Generation of electricity from renewables during periods of low demand where there is an excess of generated renewable energy is not uncommon. A method to counter this problem would be to deploy electrical storage facilities. The excess energy generated can be stored in the storage facility and extracted when there is a demand to be met.

This thesis will investigate the use of a seawater pump hydro storage facility as a storage solution for a proposed tidal stream generation facility. The feasibility of using a PHS to produce a base load profile from the tidal array will be studied. A base load is defined as the minimum electrical demand an energy generation technology can produce over 24hours.

Methodology

The purpose of this thesis is to investigate the technical feasibility of using a pump hydro storage (PHS) facility as a means of storing energy produced by a proposed tidal stream to achieve a base load profile.

A brief description of the technology to be used is discussed in the early chapters of this thesis.

A site investigation by looking at contour maps was carried out to look for possible areas to deploy a seawater PHS facility. The main criteria for possible sites is the presence of high level ground close to the shores to make use of the sea as a lower reservoir. A reservoir-sizing tool was developed and by using this tool, the amount of potential energy in a given reservoir of known volume and height can be found.

Modeling of the proposed tidal stream energy project was carried out to investigate the potential output of the system. A modeling by using a PHS to create a base load profile from the tidal array was carried out.

Pump Hydro Storage

The concept used in PHS schemes is rather simple. Water in a reservoir of a given height has potential energy. When the water flows down either through a stream or a tube (also known as penstocks), it has a velocity due to gravitational acceleration and this flowing water has kinetic energy. This kinetic energy can then be harvested and converted into electricity by the use of a turbine generator [1]. The height between where the water starts to flow and the turbine is known as the head height. At times of the day when the cost of electricity is low, pumps or pump turbines can be used to pump water into the upper reservoir for later use. Besides just relying on off-peak electricity to fill the upper reservoir, excess energy generated by intermittent renewable energy sources can be used, thus making the facility act as storage for unused electricity [2]. This further balances the supply and demand of electricity thus ensuring that renewable energy is not put to waste.

The first PHS power plant was the Herdecke Pumped Storage Power Plant in Germany, which was authorised in 1930. However, in 1980, a broken pump ultimately caused the plant to close. About five years later a utility company called RWE constructed a new PHS system adjacent to the power plant that was shut down. The Herdecke plant was retrofitted with modern equipment in 2007. When the PHS system is pumping water into the upper reservoir, it uses about 153,590kW, whereas when it is generating, it creates 153,000kW. Notice that only about 600kW extra is used to pump water back to the upper reservoir. The efficiency of this PHS system is 75% [3]. It has an upper reservoir with a volume of about 1.5Mm^3 and a head height of 145 m to 165 m. The total energy capable of being stored is 590MWh [4].

Turbine used in pump hydro storage

For the purpose of this thesis, we will only be looking at PHS systems that use a pump turbine. A pump turbine is a turbine that acts as a generator and a pump as one unit. The figure below illustrates how these pump turbines are generally set up.

Figure 1 – Pump turbine in its turbine hall [5]

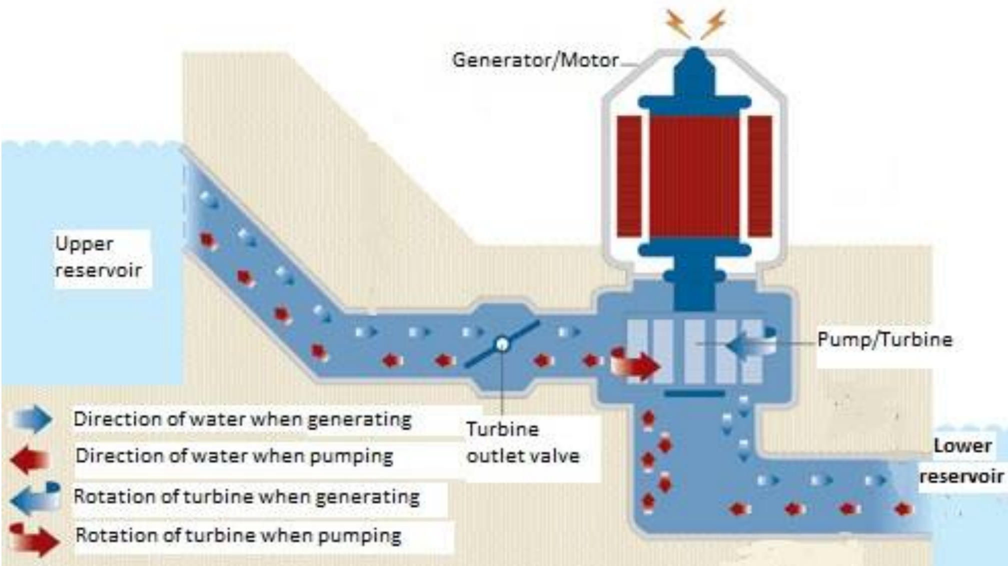

Figure 2 – Schematic of water flow through the pump turbine [6]

Figure 1 illustrates how a pump turbine would be set up in a PHS facility. Figure 2 shows a schematic of how the water flows with respect to generating and pumping. When generating, electricity is fed into the grid. Electricity is drawn from the grid or from excess renewable energy generation in order to pump water into the upper reservoir, using it to store energy in the form of gravitational potential energy.

Why pump hydro storage?

There are many reasons for using PHS as a storage solution. One of which is that there are no air pollutants released when generating energy, thus it does not contribute to climate change. PHS systems are capable of almost instantaneous starting, load variation and stopping, which further improves power reliability. Unlike many large-scale storage solutions, a PHS facility has a long useful life expectancy, capable of functioning for over 50 years. To add to this advantage, over its lifetime, the average cost of operation, generation and maintenance is low compared to other sources of energy [1].

PHS allows the integration of intermittent energy sources, such as solar and wind to ensure the excess energy produced does not go to waste. This solution allows for higher levels of grid energy storage, thus increasing opportunities to deploy more renewable energy systems. This storage solution is able to balance energy supply and demand hence maximising the use of intermittent renewable generation resources. PHS ensures stability and reliability is secured for all consumers [2]. PHS can be designed in a way that it does not require an external power supply to start operation; this process is called black starting [7].

Around Scotland

Scotland currently has two PHS facilities in operation. Cruachan Dam, which is located in Argyll and Bute, and Foyers, located near Loch Ness. Cruachan power station in itself is historical as it was the first PHS to use a pump turbine generator in the world [8]. This indicates that it was the first PHS facility to use a turbine that acts as a pump and generator as a single unit, whereas its PHS predecessors had separate components to generate energy and to pump water. Cruachan was built in the beginning of the 1960s and five years later, the Queen of the United Kingdom officially opened it. Cruachan's turbine hall was built within the hollowed-out rock of Ben Cruachan for which 220 000m^3 of soil and rock had to be excavated. This in turn allowed the scenic landscape to be preserved, the visible sections of the power station from the road consists of a 316m long dam at the peak of the mountain, offices and visitor facilities. As for generating electricity, Cruachan is fitted with four generators, capable of generating a total of 440MW. Each generating unit can reach full load within 30seconds. This is achievable as Cruachan has a head height of 396m. The upper reservoir of Cruachan has the capacity to hold 10million cubic meters of water. There are networks of 19km of tunnels and pipes that diverts rainwater coming from streams into the upper reservoir. Besides just being used as a PHS plant, it can also be used as a conventional hydro plant where run-off water coming from its upper reservoir contributes to 10% of the electricity produced at Cruachan. [9]. A schematic of the Cruachan PHS station can be seen in figure 3 below.

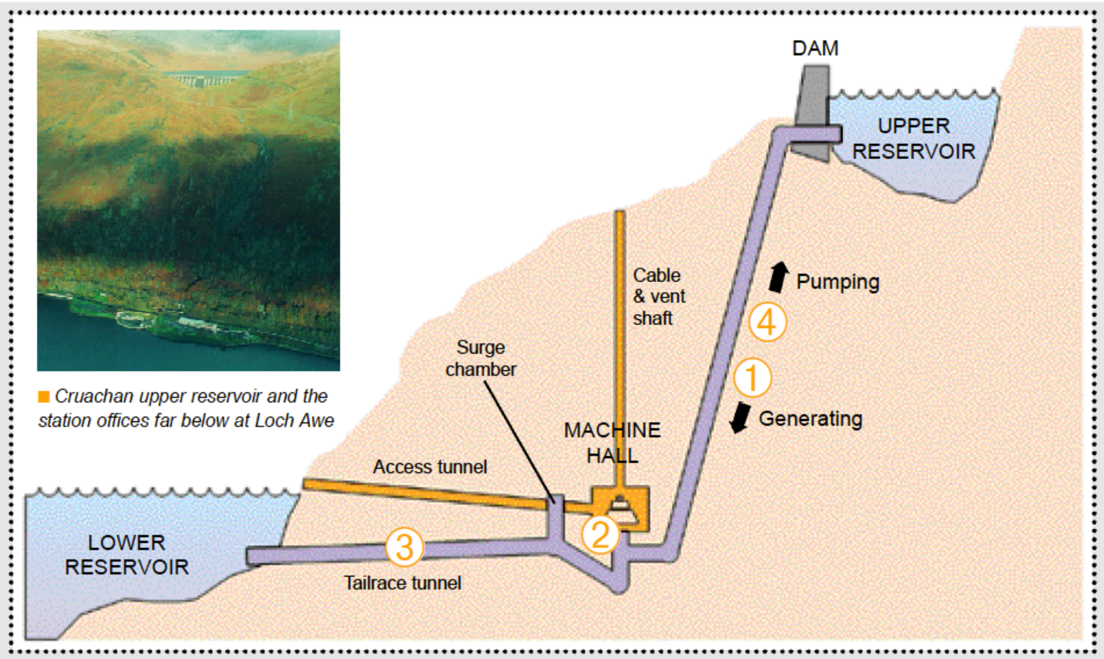

Figure 3 – A layout of the Cruachan PHS scheme [9]

"*Cruachan power station represents an outstanding feat of engineering achievement and continues to provide the much needed flexibility to meet the UK's electricity needs at short notice.*" – Station manager Bob Wales, 2012 [10].

Foyers pump storage scheme was initially a conventional hydroelectric station, which was constructed by Alcan during the mid 1890s. It was intended to produce energy for an aluminium smelter. The hydroelectric station comprised of six 500KW turbines. When the smelter closed down in 1968, Scottish Power purchased the station and re-designed it to become a PHS station. However, at the original scheme, an upgrade to a 5MW turbine was undertaken, meaning that even after upgrading to a PHS system, the original hydroelectric station still remained functioning. In order to construct the Foyers PHS scheme, a new power station had to be built adjacent to the existing hydroelectric station. Steel lined tunnels with 5m diameters were driven into 4km of porous rock. Besides that, new turbines and generators, along with transmission lines were upgraded to handle the additional power. Once upgraded, the PHS system was capable of generating 300MW from two 150MW generators. In order to meet peak demand, the machines are kept running during the day on spinning reserve, the impressive response time of the station to meet demand is in the order of 15s. In order to keep the turbines at a state of readiness, power is taken from the 5MW hydroelectric station [11].

Case Study

The case study investigated is the Okinawa Seawater Pumped Storage Power Plant, located in Okinawa, Japan. This PHS plant is the first of its kind to use seawater as a means of storing energy; it was a demonstration plant to prove this type of PHS works [12]. The research and surveys with regard to environmental and technical aspects when utilising seawater started in 1981 and took six years to complete. Feasibility studies indicated that a seawater PHS plant was favourable and so in 1991 construction began and was completed in 1999.

Fresh water resources are scarce on the little island of Okinawa, which implies that a conventional PHS that uses fresh water is not viable. There are mountainous regions on the northern section of Okinawa, which makes it the perfect site to build a seawater reservoir in order to feed the PHS. The figure 4 below illustrates the layout of the selected site and figure 5 shows the cross section of the PHS system.

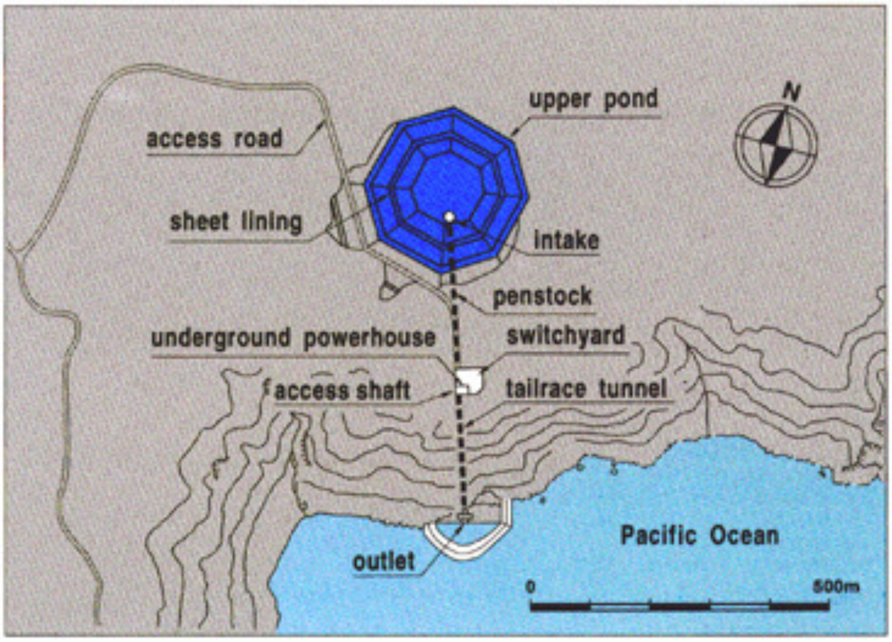

Figure 4 – Layout of Okinawa PHS system [12]

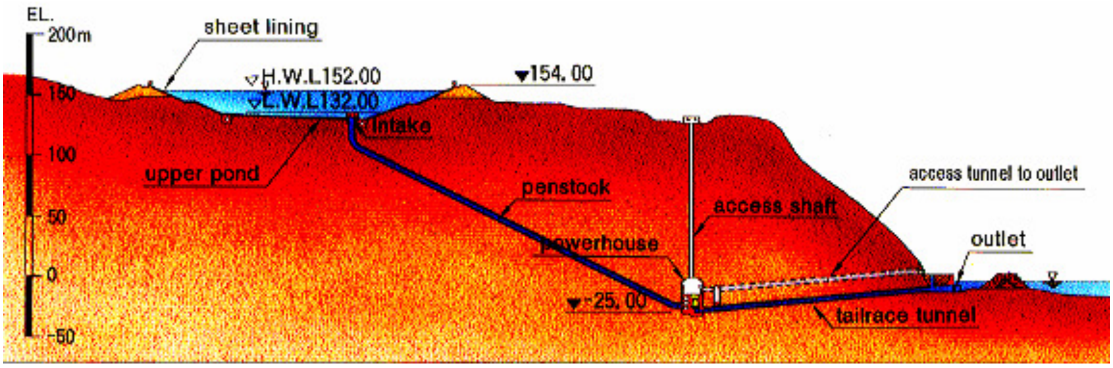

Figure 5 – Cross section of Okinawa PHS [12]

The specifications of the PHS are listed in table 1 below.

Item			Specification
Power Plant	Name		Okinawa Yanbaru Power Plant
	Max. output		30 MW
	Max. discharge		$26m^3/s$
	Head height		136m
Upper Reservoir	Type		Excavated, Rubber sheet-lined
	Max. embankment height		25m
	Crest circumference		848m
	Max. width		251.5m
	Max depth		22.8m
	Total storage capacity		0.59×10^6 m^3
Water path	Penstock	Inner diameter	24m
		Length	314m
	Tailrace	Inner diameter	27m
		Length	205m

Table 1 – Specifications of Okinawa seawater PHS system [12]

The upper reservoir is located about 600m from the shore, on the Pacific Ocean side of Kunigami Village and is approximately 150m above sea level.

As this PHS system was the first of its kind, extensive research on the environmental impacts were carried out, most of which started in 1982, long before the construction began. An environmental impact assessment was compiled in 1989 and its scope can be found in table 2.

Environmental impact assessment scope		
Weather, Meteorology, Air quality, Water quality, Noise, Vibration, Offensive odour, Soil contamination, Topography, Ground settlement, Sea current, Marine phenomenon		
Salt spray, Seawater seepage		
Plant	Rare plants, Vegetation, Soil profile, etc.	
Animal	Terrestrial animal	Mammals, Reptiles, Birds, Amphibians, Insects, Soil fauna
	Aquatic organisms	Gully animals
	Marine organisms	Coral, Fishes, Benthic organisms, Eggs and fry, Plankton, Tideland organisms, Seaweed

Table 2 – Scope of environmental impact assessment [12]

The major environmental impact that could cause alarm is the damaging effect of salt spray onto the environment as seawater is being pumped. Lab tests were carried out, which included a wind tunnel water tank tests; and numerical simulations were undertaken with regards to salt spray. The tests and simulations concluded that there were negligible differences to effects experienced from the amount of salt spray coming naturally from the sea.

As for the flora, it was found that on land there were many native species potentially involved, and as for the sea reef-building coral were found to be significant. In terms of fauna, 16 rare species of animals were discovered, of which, five were categorised as endangered and seven listed as threatened according to the Red Data Book. In accordance, a Study Committee for the Protection of Invaluable Assets mainly consisting of local specialists was organised in 1989. From the findings of the committee, Fundamental Principles of Environmental Conservation were drawn. The list is as follows:

1) The inhabitants of the project area are the natives; therefore they should be given consideration with modest attitudes.
2) The area to be developed should be at the smallest possible to ensure the ecosystem is not too disrupted.
3) The scope of implementing measures should not be limited to just the construction area, it must be applied to the surrounding environment as well.
4) If any damage is to occur in the environment it must be restored with minimal delay.

Based on the scope listed, environmental impacts were then extracted and are as follows:

1) Outflow of muddy water that comes from the construction site into gullies and seascape close to the river mouth.
2) Loss of habitat area as topography is altered.
3) Vibration and noise arising from heavy equipment.
4) Danger to small animals as damage may arise from construction vehicles and accidents from falls.

From the environmental impact assessment carried out, mitigation measures were drawn to help reduce the scale of these impacts. These measures are listed in table 3 below.

<table>
<tr><th colspan="2">Environmental impact factor</th><th>Mitigation measure</th></tr>
<tr><td rowspan="2">Outflow of muddy water that comes from the construction site into gullies and seascape close to the river mouth.</td><td>Construction water</td><td>• Chemical treatment using turbid water plant</td></tr>
<tr><td>Turbid water from red soil</td><td>• Chemical treatment using turbid water plant
• Reduction of turbid water by separating into clear water and red water
• Reduction of red water through spraying asphalt emulsion or seeds on exposed ground
• Installation of gabion weir at downstream section of gully</td></tr>
<tr><td rowspan="2">Loss of habitat due to topography alteration</td><td>Reduction of area altered</td><td>• Layout of powerhouse and watercourses underground
• Omit access road and work entrances to outlet and power station
• Minimise construction area by balancing cuts and embankments where possible</td></tr>
<tr><td>Protection and restoration of vegetation</td><td>• Sculpt and green site of construction with no delays
• Protect existing forestry by planting trees what are low-height</td></tr>
</table>

Vibration and noise from heavy equipment	• Prohibition of constructing at night • Use of low-noise machinery • Low speed limits within construction area
Danger to small animals as damage may arise from construction vehicles and accidents from falls	• Capture and removal or animals and plants within construction area • Install facilities (intruder prevention nets) to prevent rare animals from entering site • Public relations activities by posters, lectures, meetings, etc. to raise awareness • Accident prevention measures by installing sloping side wall gutters

Table 3 – Environmental impact and mitigation measures [12]

As seawater creates a corrosive environment it will damage conventional pump turbines, therefore a new type of pump turbine had to be developed. The development and survey program was carried out by Electric Power Development Co., Ltd [13]. The seawater pump turbine was constructed in a manner that the runner is removable from below to ease disassembly and reassembly. Figures 6 illustrates the seawater pump turbine developed and figure 7 shows a cross section of the pump turbine and its components. The methods used to prevent corrosion of individual components are listed in table 4.

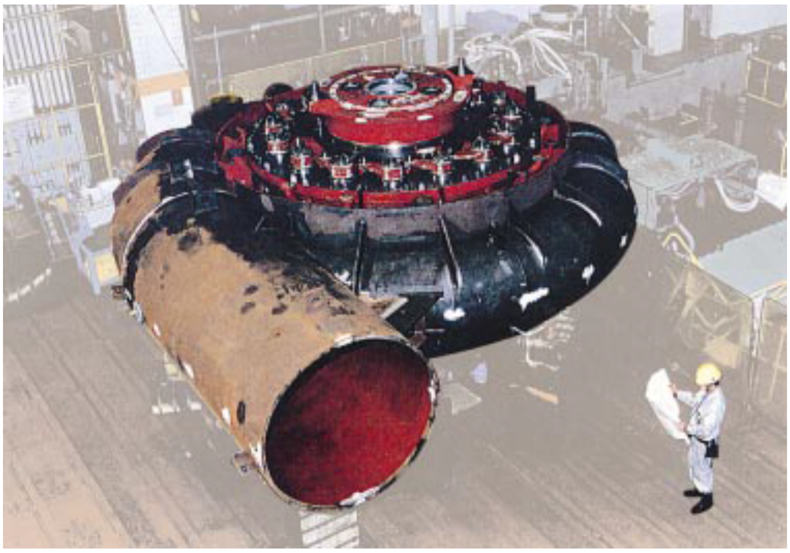

Figure 6 – Appearance of pump turbine during shop assembly [13]

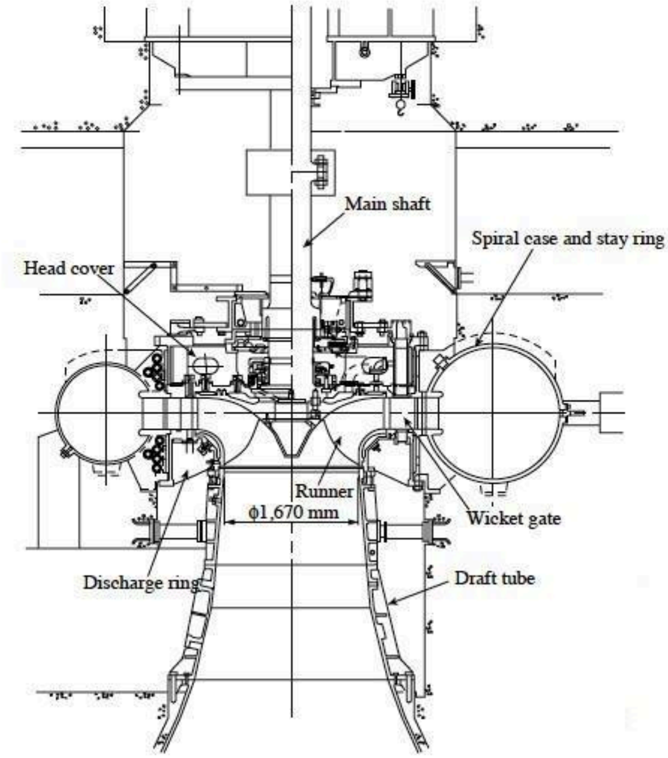

Figure 7 – Sectional view of pump turbine [13]

Component	Corrosion prevention method
Main shaft sealing box	• Ceramics applied to sealing element • Drain pipes are provided up to drain pits thus preventing water leakage on the head cover
Wicket gate stem bearing assembly	• Wicket gate stem packing is doubled, preventing seawater from entering the bearing housing • Wicket gate stem is replaceable without disassembling the head cover and discharge ring
Wicket gate seal packing	• Furnished with seal packings • Seal packing usually held by a separate packing gland • Rubber packing of seawater pump turbine is jointed to a stainless steel base by rubber moulding process (Figure 5)
Main shaft and runner	• Connection joint between main shaft and runner is entirely sealed by rubber gaskets, isolating seawater from coupling bolts

Table 4 – List of components and corresponding corrosion prevention methods [12]

It is not just the components that may suffer damage due to seawater; the materials that are used in the construction of the components were taken into account. To do so, the corrosive resistance of materials and economical evaluation were considered. Mild carbon steel coated with paint is used at low-flow velocity portions. To prevent corrosion as a result of paint damage and against crevice corrosion, cathodic protection was applied. The rate of corrosion is accelerated as flow velocity increases; the cathodic protection is designed to be conducted by external power sources to allow the adjustment of corrosion preventive current. The components and their respective materials are listed in table 5 below.

Component	Material
Spiral case and stay ring	• Rolled steel used for welded structures • Water passage surface coated with vinyl-ester-type, extremely thick film of paint with glass flakes
Head cover and discharge ring	• Water passage surface made from austenitic stainless steel with low carbon content • Surfaces that do not get wet are made out of rolled steel for welded structures
Wicket gate, runner, and main shaft	• Wicket gate and runner made from austenitic stainless steel casting with low carbon content includes nitrogen • A slip ring is provided to the main shaft to allow preventive current for cathodic protection • Main shaft made from stainless steel for the pressure vessel comprising nitrogen in austenitic group
Draft tube	• Upper sections of the upper draft tube liner is made from austenitic stainless steel with low carbon content • Other sections made from rolled steel for general structures and are coated with vinyl-ester-type, extremely thick film of paint with glass flakes
Main shaft sealing box	• Seal made of ceramics • Other parts made from austenitic stainless steel with low carbon content • Space between main shaft and sealing box is narrow, therefore the sacrifice electrode system is adopted as corrosion prevention

Table 5 – List of components and their material composition [13]

It is not just the damage that can be caused by the corrosive nature of seawater that is taken into account; methods to prevent adhesive marine organisms were investigated. An example of a marine organism adhering to all components exposed to seawater is the barnacle. Barnacles stick to substances when the flow velocity is less than 5m/s, and most easily in low velocity flows, between 1 and 2m/s. As adhesion of barnacles reduces efficiency of the pump turbines and leads to clogging of piping and other failures, this problem is taken into consideration where water flow seems to be stagnant. For this reason, pump turbine components should be coated with anti-pollutant dirt-prevention type paint that can repel water to prevent the growth of barnacles and other adhesive marine organisms.

As a result of proper planning and research being carried out, this first example of a seawater PHS proved that using seawater is viable and safe to be used in the environment.

Tidal Energy

A tide is referred to as the rise and fall of sea levels relative to the shore. The tidal movement exists due to the gravitational pull of celestial bodies, mainly the sun and the moon. If the earth were covered entirely in water, tidal ranges would be small. As the earth has landmass, it creates large ranges in certain parts of the world. In most regions of the world, tides occur twice a day, two high tides and two low tides. The horizontal movement of water in response to gravitational forces is known as tidal currents [14]. Tidal energy is abundant in the UK, localized sites which include Orkney and the Pentland Firth. Tidal energy depends on the tidal currents that move with a certain velocity, with the flow of the tides; tidal turbines can be put in place in order to extract the energy.

The method tidal turbine devices use to harness this form of tidal energy uses the same concept as wind turbines. A flow of fluid with a given velocity passes through the turbine blades, which then turn the turbine that generates electricity. An example of how tidal turbines may be placed on the seabed can be seen in figure 8.

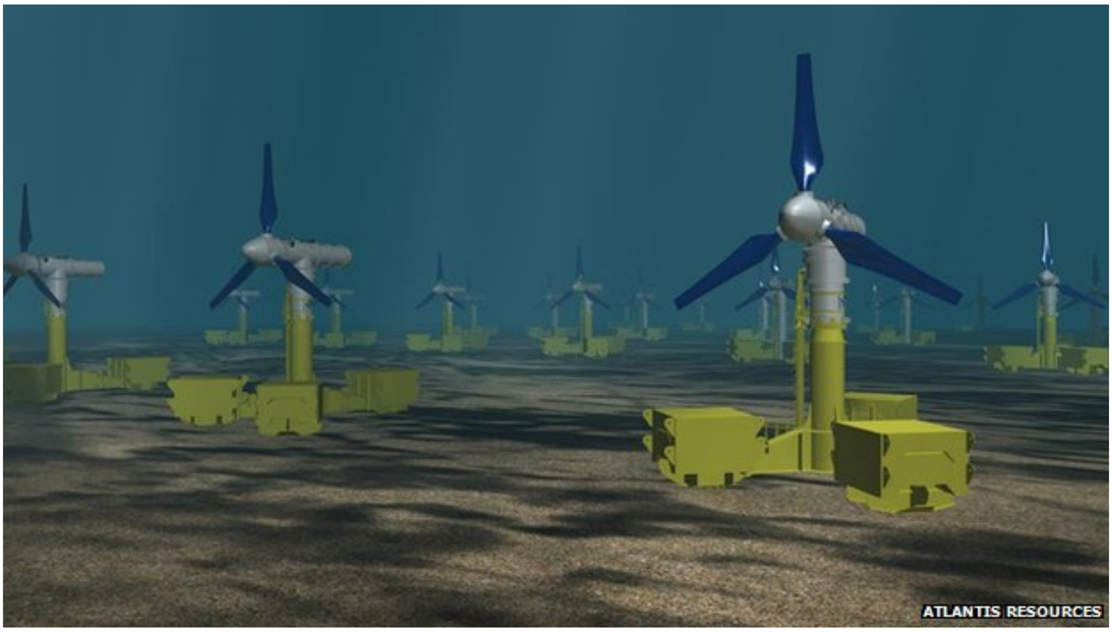

Figure 8– An artist’s render of how the tidal turbine system would look like [15]

Though wind turbines and tidal turbines share some similarity, they have one major difference. The flow of wind is highly probabilistic; therefore determining when energy can be produced is a challenge. However, this is not the case for tidal turbines as tidal current velocities are deterministic by means of gravitational theory, they are cyclic and predictable [16]. This is a great advantage as the amount of energy that generated can be determined out of a system in a given time of the day. In order to make accurate predictions of tidal energy, these stages should be used:

1) Have long term time series of tidal current velocities
2) Determine the corresponding turbine power curve
3) Apply power curve to a time series to determine the yield of the device

There are many benefits of harnessing tidal energy in the UK, one of which is the security of supply. Tidal energy only depends on tidal currents in specific locations chosen and does not require any external sources of fuel to generate electricity. As more devices are deployed, the cost of energy would be expected to fall. Tidal stream energy resources around the UK are estimated to be 95TWh/year. Of this estimated energy, 18TWh/year of tidal stream energy was assessed and deemed economically recoverable by means of modern technology [17].

A potential problem of harnessing tidal energy is that the time when the tides have high velocities, and a lot of energy is generated, might be a time when the demand for energy by the grid is low [14]. Another problem associated with large capacity tidal energy systems is power transmission. However, development of high voltage lines has partly resolved this issue.

In Scotland

As mentioned in the previous section, there is a lot of tidal stream energy potential in the UK, and most of it is in Scotland. The Atlas of UK Marine Renewable Energy gives an indication of the areas around Scotland that have tidal energy potential. This can be seen in figure 9 below.

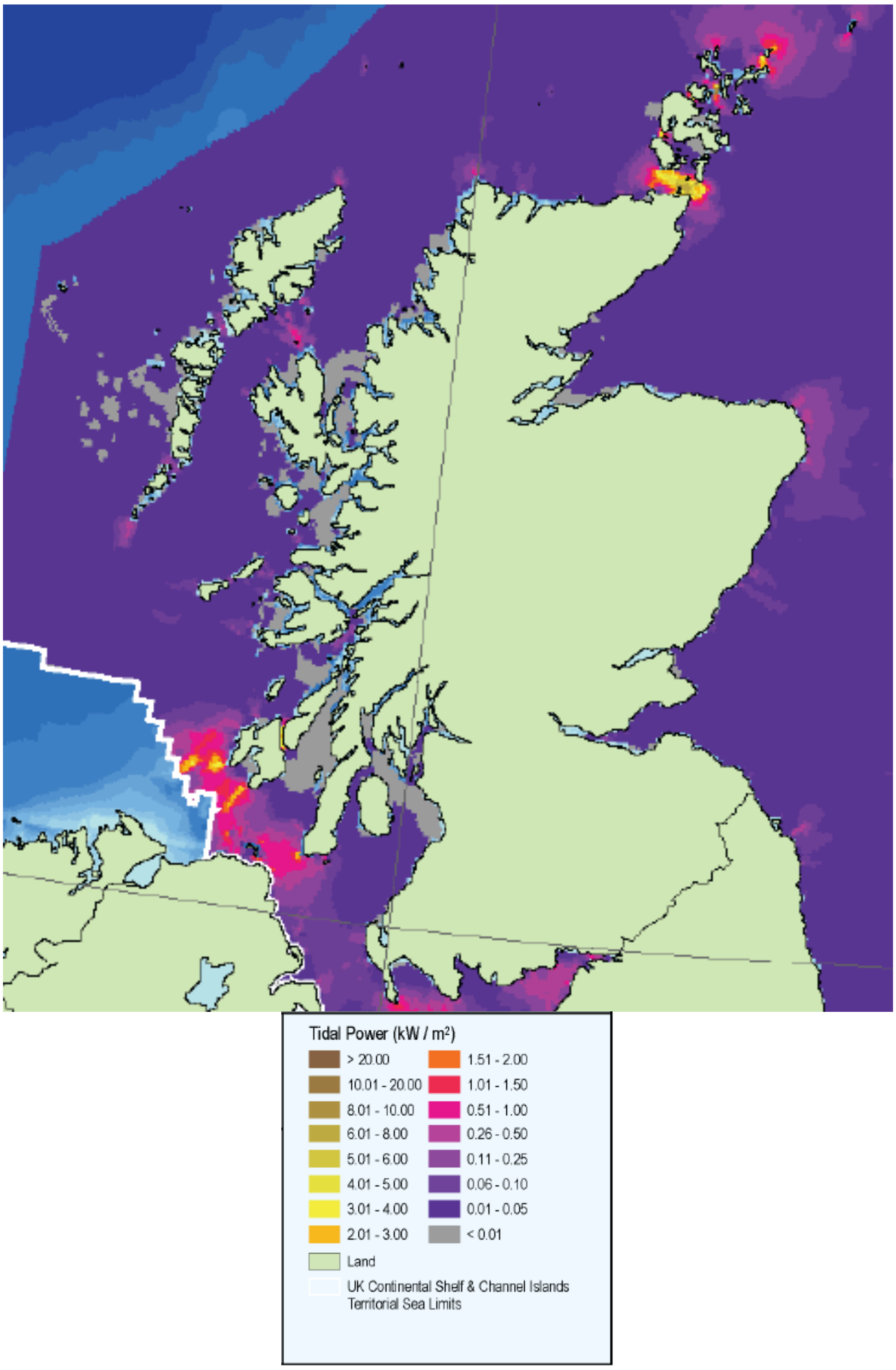

Figure 9 [18] – Potential of tidal energy around Scotland

As seen in figure 9, there is a lot of tidal energy that can be harvested in the Northern areas of Scotland, specifically in the Pentland Firth and Orkney. Figure 10 is an enlargement of this section on the map seen in figure 9.

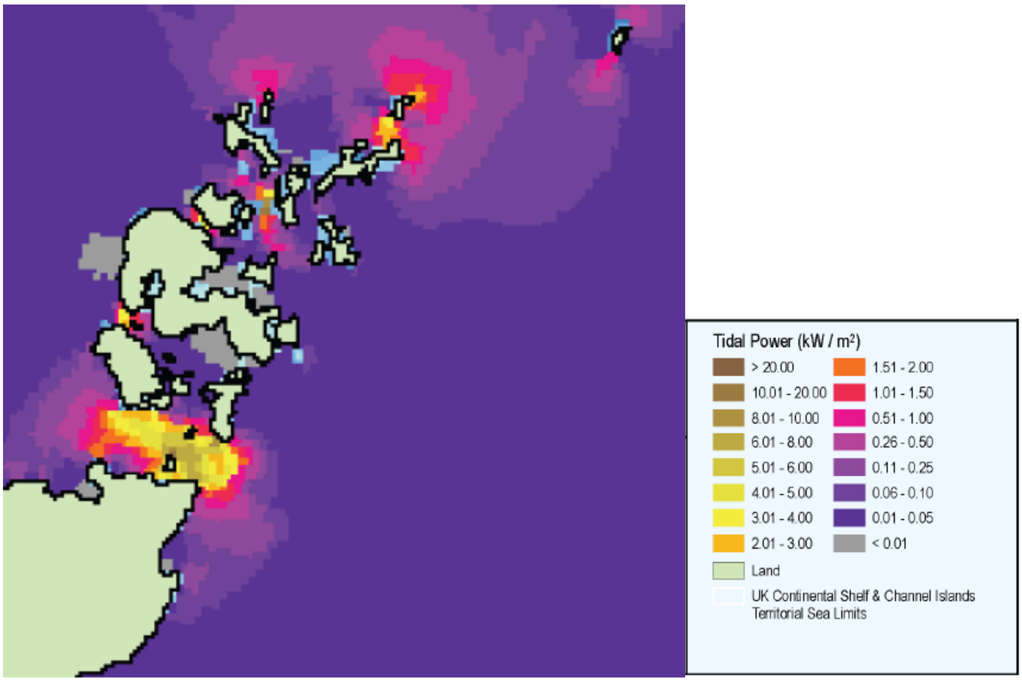

Figure 10 – Tidal potential around Orkney [18]

The largest area shown here with high potential for deployment of tidal turbines is the Pentland Firth. It was reported that if tidal energy were to be harvested in the Pentland Firth, where the tidal currents is some of the fastest in UK, it could provide power to meet half of Scotland's electricity demand [19]. Engineers from Oxford and Edinburgh Universities stated that if a tidal energy system were to be installed in the Pentland Firth, it could generate up to 1.9GW of renewable energy, which is equivalent to 43% of Scotland's current electricity consumption [19]. The UK Crown Estate has identified sites that cause minimal impacts to sea life and shipping in the Pentland Firth.

A major tidal energy system is set to begin construction in the Pentland Firth later this year. The company that would be constructing the system is Atlantis, and the name of the project is MeyGen. Upon completion of the tidal energy system, it would have around 269 tidal turbines submerged on the seabed. When completed, the tidal scheme would be able to generate a total of 398MW [15]. The device that is to be installed is illustrated in figure 11. The device will be installed in the Inner sound of Pentland Firth, the stream of water between Stroma Island and the Scottish mainland [20].

Figure 11 – Tidal stream turbines to be installed into the Pentland Firth [15]

The Highlands and Islands Enterprise director of energy and low carbon, Callum Davidson quoted – *'The Inner Sound of the Pentland Firth has first class tidal resources, appropriate current speeds and crucially the site has good access to the grid.'* [15]

A report that was commissioned by The Crown Estate and prepared by BVG Associates in May 2011 indicated the predicted future deployments of tidal energy resources in the Pentland Firth and Orkney. These predictions can be seen in figure 12. From the figure, it is predicted that 1.5GW of cumulative installed capacity of tidal stream energy will be achieved by 2020

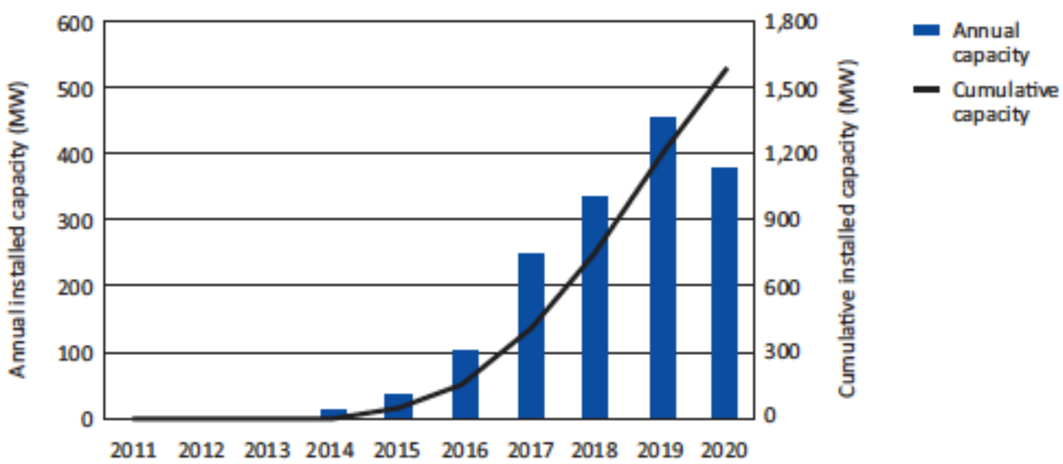

Figure 12 - Predicted deployment plan for Pentland Firth and Orkney tidal streams [21]

Why Integrate Pump Hydro Storage and Tidal Energy?

Even though tidal energy harvesting is highly predictable, the periods the tidal system generates does not necessarily match the demand of electricity. For this reason, it is important to have a good energy storage solution for utalisation of the harnessed tidal energy. As both PHS and tidal energy systems do not contribute to the increase in green-house gasses, the combination of these technologies contributes to decarbonising the environment. As a storage technology, PHS does not require any fuel or chemical processes to function, thus it is safe and does not harm the environment. With the development of seawater pump turbines, it is now possible to set up a PHS system in areas where tidal energy systems are to be deployed. The need to look for a lower reservoir is now eliminated and the only component needed would be the upper reservoir, which can be placed by building a dam on higher ground close to the shore.

With this in mind, a site selection process was carried out and further explained in the next section.

Site Selection

A survey of the geographical landscape around the Pentalnd Firth was carried out to investigate potential sites to deploy the PHS system to be connected to the proposed tidal energy array in the Pentland Firth. The main criteria that were considered are the presence of high ground close to the shores around Pentland Firth and the ease of connection to the national grid. With these criteria in mind, two sites appeared to show potential for the deployment of a seawater PHS system.

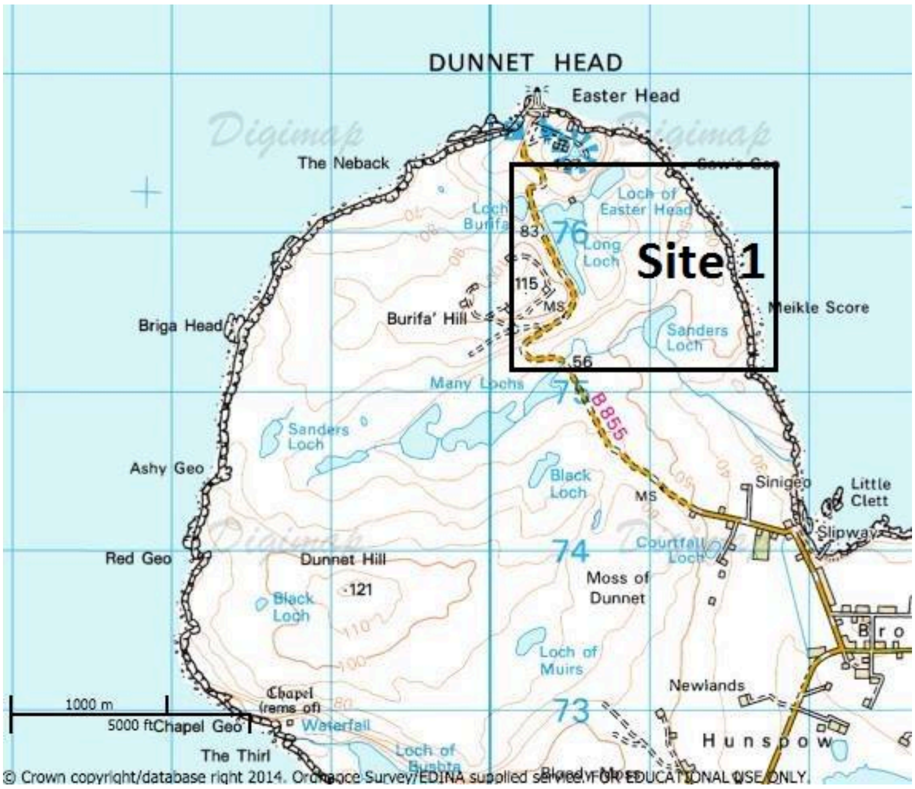

Figure 13 - Map view of Dunnet head

Figure 13 shows the contour layout of Dunnet head, which is about 10km from the Pentland Firth. Site 1 is located within the black box in figure 13. From the detailed study of the topographic arrangement in certain sections of the selected site, an area where it would be plausible to deploy a seawater PHS system was identified and can be seen in figure 14.

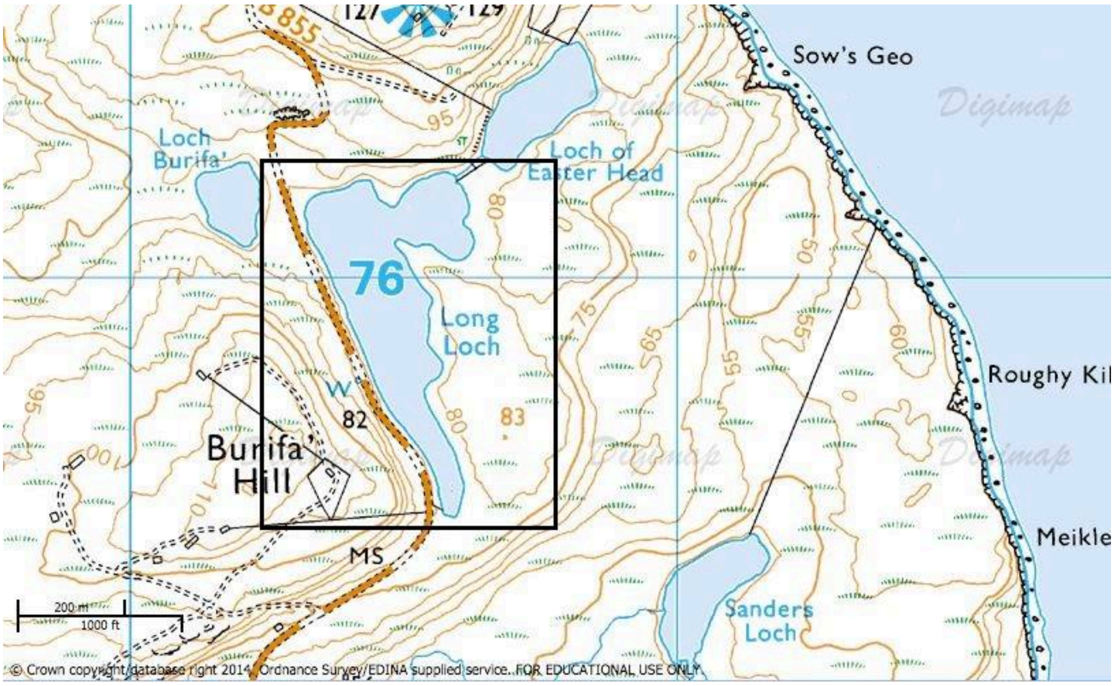

Figure 14 – Potential site for PHS system

As it can be seen on the contour lay out in figure 14, there are lochs in high ground that can be used as an upper reservoir for the proposed PHS system. The loch that will be examined is Long Loch, noted in the black box in figure 14. Using a built in measuring too, the surface area of Loch Long can be identified as shown in figure 15.

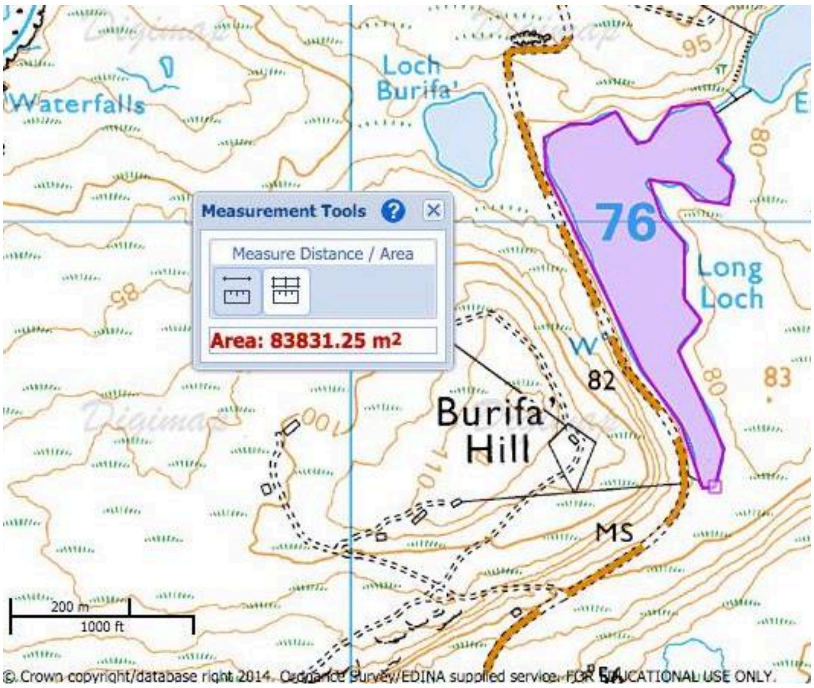

Figure 15 – Surface area of Long Loch

The surface area of Long Loch is taken to be 83800m^2. However, information on the depth of Long Loch is unavailable. The depth of Long Loch will be assumed to obtain the volume of Long Loch in the later sections.

Besides Dunnet, another potential site where connectivity to the electricity network is not a large problem was identified. The site is located on the Scottish mainland in Thurso, about 30km from the Pentland Firth and can be seen in figure 16 and 17.

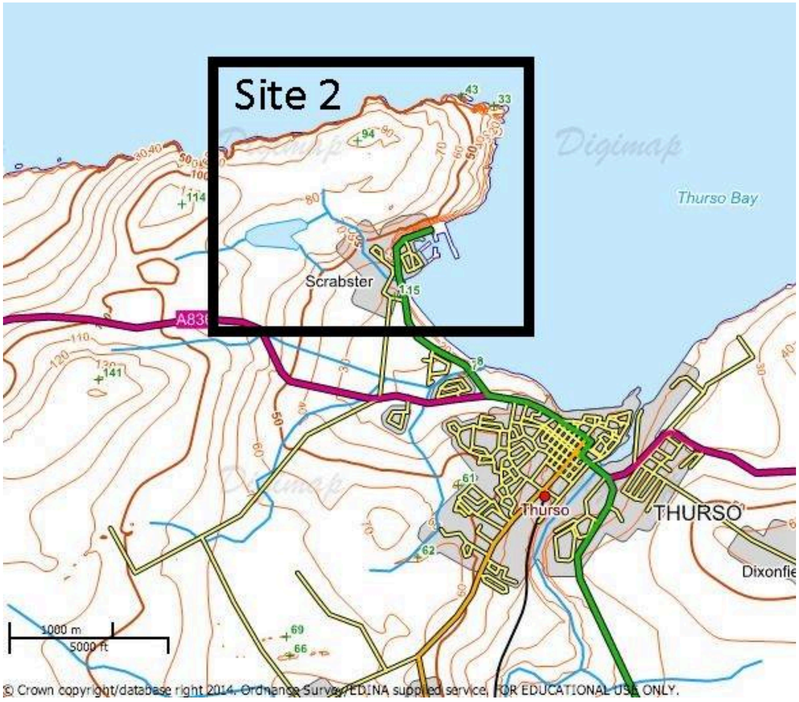

Figure 16 – Potential site near Thurso

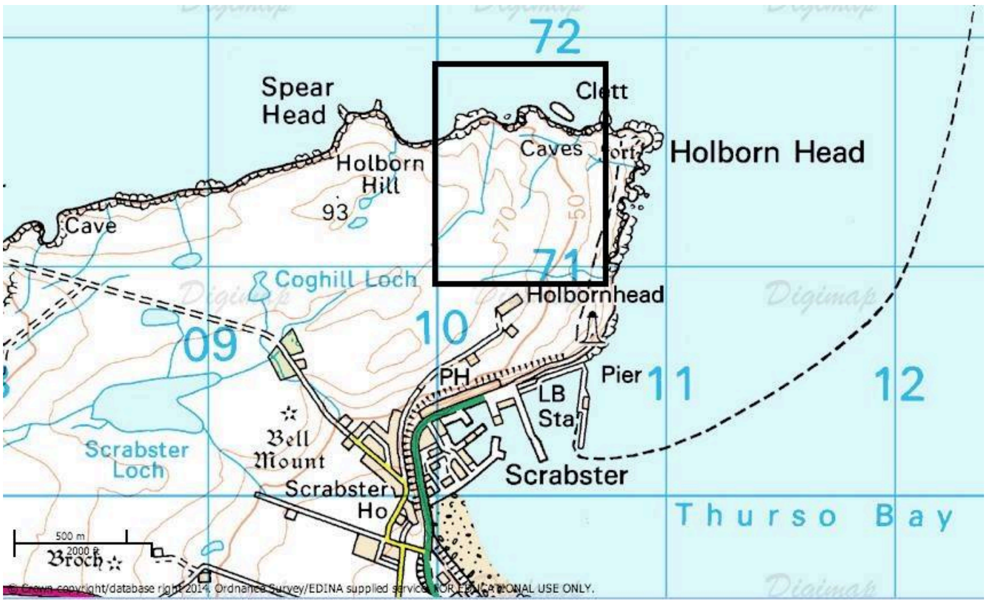

Figure 17 – A closer perspective of site 2

Figure 16 shows the potential site chosen in Thurso, which is close to Thurso bay. Figure 17 is a magnified view of the chosen site. Site 2 does not have very high-level grounds due to the topographic nature of the surroundings. A potential area to deploy the reservoir of the seawater PHS was identified. Unlike site 1, a loch will not be used as an upper reservoir. Scrabster Loch will not be used as a reservoir as it is the source of water for waterfalls in the area surrounding the loch. In its place, a built reservoir will be examined to compare the two PHS systems. A level area 50m above sea level was chosen to be the base of the reservoir and an 80m high ground was chosen to be the back section of the reservoir. In order to have a reservoir in site 2, a dam has to be built connecting the 80m hill and 50m hill and it will be 30m high. This is illustrated in figure 18.

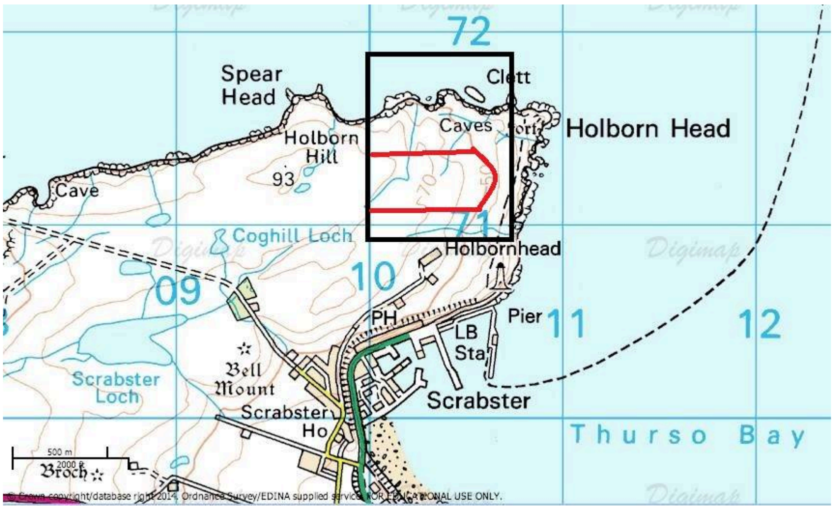

Figure 18 – Dam walls to be built on site 2

If a reservoir were to be built in site 2, it would have the added advantage of having a stream of water flowing into it thus increasing the amount of liquid being stored without having to pump liquid up into the reservoir.

PHS reservoir sizing and predicted output from pump turbine tool

As the size of the upper reservoir is an important factor when wanting to deploy a PHS system, a simple tool was developed using excel. Within the tool, the user is able to predict the output from pump turbines.

In order to find the storage capabilities of the upper reservoir, the volume of liquid that is required to fill the reservoir has to be determined. The equation below is to find the volume of water in a container that has linear sides.

$$Volume\ (m^3) = Length(m) \times Breadth(m) \times Height(m) \qquad (1)$$

To calculate the amount of energy the reservoir can store, the following calculations were used.

$$Potential\ Energy(J) = mass(m) \times gravitational\ acceleration\left(\frac{m}{s^2}\right) \times head\ height(m) \qquad (2)$$

In order to calculate the mass of fluid in the reservoir, the equation below was used.

$$Mass\ (kg) = Volume(m^3) \times Density(\frac{kg}{m^3}) \qquad (3)$$

Once the potential energy is calculated, as the units are in Joules, to convert the energy to kWh, the following relation was used:

$$1\ Joule = 2.78 \times 10^{-7} kWh$$

To calculate the theoretical power available from falling water, equation (4) was used:

$$P = \eta \times \rho \times q \times g \times h \qquad (4)$$

Where P is power (W), η is turbine efficiency (%), ρ is density (kg/m^3), q is water flow rate (m^3/s), g is acceleration due to gravity (m/s^2) and h is head height (m).
The tool developed is limited to solving the volume of a given reservoir, as it can only calculate the volume if the selected site has linear sides and is in the shape of a square or rectangle. It does not take into account calculating the volume for containers that are uneven. However, if the volume of an irregular shaped container is known, the value of the volume can be inserted directly in to the tool.

Proposed Pump Hydro Storage System to be Built

Now that plausible sites have been chosen, certain characteristics of the site have to be known in order to know the possible energy output or storage potential. The main characteristics include head height and size of reservoir.

Site 1

As noted in the site selection section, Long Loch will be used as an upper reservoir for the proposed PHS system. Table 6 shows the measurements of the loch and assumptions made for the depth and head height of the PHS.

Components	Measurement
Surface area of Long Loch	83800m^2
Assumed depth of Long Loch	10m
Height above sea level of Long Loch	80m
Head height of PHS	70m

Table 6 – Measurements of potential reservoir components

Using the measurements listed in in table 6, the volume of the reservoir was found to be 838000m^3.

Density of salt water depends on the salinity and the temperature of the seawater. As these values fluctuate throughout the year, for simplicity of calculations, an average value for the density of salt water is to be used, 1027kg/m^3.

Using the storage capacity tool, the result of a system with these characteristics was found and can be seen in figure 19.

To calculate the storage capacity of a pumphydro system, we need to find the following:

1) Volume of reservoir
2) Mass of liquid in reservoir
3) Potential energy of the fluid in a reservoir at a given height

VOLUME OF RESERVOIR

Equation for a container with linear sides, Volume = Length x Breadth X Height

Length (m)	0
Breadth (m)	0
Height (m)	0
Volume (m^3)	0

MASS OF LIQUID IN RESERVOIR

Mass = Volume x Density

Volume (m^3)	838000
Density (kg/m^3)	1027
Mass (kg)	860626000

POTENTIAL ENERGY STORED IN RESERVOIR

Potential Energy = Mass of Liquid in Reservoir x Gravitational Acceleration x Head Height

Mass (kg)	860626000
G. Acceleration (m/s^2)	9.8
Head Height (m)	70
Potential energy (J)	5.90389E+11

As potential energy is in Joules, we have to convert it to kWh

1 Joule is equivalent to 0.000000278 kWh

Energy (J)	5.90389E+11
Power (kWh)	164128.2632

Figure 19 – Results obtained from storage capacity calculator tool for site 1

Therefore the maximum amount of storage capacity this configuration of seawater PHS system may have is about 164MWh.

Site 2

The head height for site 2 is taken to be 50m. Just as in site 1, as the proposed reservoir does not have linear sides, the calculations used are estimates. The components and their measurements can be seen in table 7.

Characteristics	Measurement
Dam wall length	450m
Dam wall breadth	460m
Height of dam	30m

Table 7 – Characteristic and measurements for reservoir in site 2

As seawater is to be used in this system as well, the density of liquid is taken to be 1027kg/m^3.

Using the storage capacity tool, the result of a system with these characteristics was found and can be seen in figure 20.

To calculate the storage capacity of a pumphydro system, we need to find the following:

1) Volume of reservoir
2) Mass of liquid in reservoir
3) Potential energy of the fluid in a reservoir at a given height

VOLUME OF RESERVOIR

Equation for a container with linear sides, Volume = Length x Breadth X Height

Length (m)	450
Breadth (m)	460
Height (m)	30
Volume (m^3)	6210000

MASS OF LIQUID IN RESERVOIR

Mass = Volume x Density

Volume (m^3)	6210000
Density (kg/m^3)	1027
Mass (kg)	6377670000

POTENTIAL ENERGY STORED IN RESERVOIR

Potential Energy = Mass of Liquid in Reservoir x Gravitational Acceleration x Head Height

Mass (kg)	6377670000
G. Acceleration (m/s^2)	9.8
Head Height (m)	50
Potential energy (J)	3.12506E+12

As potential energy is in Joules, we have to convert it to kWh

1 Joule is equivalent to 0.000000278 kWh

Energy (J)	3.12506E+12
Power (kWh)	868766.2074

Figure 20 – Results obtained from storage capacity calculator tool for site 2

Results gained from the storage capacity calculator tool indicated that for the chosen characteristics in site 2, the reservoir would be capable of storing about 870MWh.

Pump turbines to be used in sites

As for the pump turbines to be used in these sites, the turbine theoretical output tool can be used to investigate the size of pump turbines that is appropriate for the given sites. The number of turbines can be manipulated by having multiple penstocks connected to the mouth of the reservoir. For this reason, the output of the pump turbines can be manipulated to give the desired outputs. After considering evaporation and conversion losses, the cycle efficiency of pump turbines is in the range of 70% to 85% [22].

Water flow through the penstocks can be manipulated to the desired flow rates. With this in mind, below are a few examples of the possible pump turbines to be deployed in site 1 and site 2.

Theoratical power available from falling water passing through turbines			
P = µ x ρ x q x g x h			
Where			
P = power (W)			
µ = efficiency of turbine (%)		Turbine efficiency (%)	0.7
ρ = density of flowing fluid (kg/m^3)		Density of liquid (kg/m^3)	1027
q = water flow rate (m^3/s)		Water flow rate(m^3/s)	10
g = acceleration due to gravity (m/s^2)		Gravitational acceleration (m/s^2)	9.8
h = head height (m)		Head height (m)	70
		Power(W)	4931654

Theoratical power available from falling water passing through turbines			
P = µ x ρ x q x g x h			
Where			
P = power (W)			
µ = efficiency of turbine (%)		Turbine efficiency (%)	0.7
ρ = density of flowing fluid (kg/m^3)		Density of liquid (kg/m^3)	1027
q = water flow rate (m^3/s)		Water flow rate(m^3/s)	30
g = acceleration due to gravity (m/s^2)		Gravitational acceleration (m/s^2)	9.8
h = head height (m)		Head height (m)	70
		Power(W)	14794962

Figure 21 - turbine sizing tool results for low and high water flow rates in site 1

Theoratical power available from falling water passing through turbines			
P = µ x ρ x q x g x h			
Where			
P = power (W)			
µ = efficiency of turbine (%)		Turbine efficiency (%)	0.7
ρ = density of flowing fluid (kg/m^3)		Density of liquid (kg/m^3)	1027
q = water flow rate (m^3/s)		Water flow rate(m^3/s)	10
g = acceleration due to gravity (m/s^2)		Gravitational acceleration (m/s^2)	9.8
h = head height (m)		Head height (m)	50
		Power(W)	3522610

Theoratical power available from falling water passing through turbines			
P = µ x ρ x q x g x h			
Where			
P = power (W)			
µ = efficiency of turbine (%)		Turbine efficiency (%)	0.7
ρ = density of flowing fluid (kg/m^3)		Density of liquid (kg/m^3)	1027
q = water flow rate (m^3/s)		Water flow rate(m^3/s)	30
g = acceleration due to gravity (m/s^2)		Gravitational acceleration (m/s^2)	9.8
h = head height (m)		Head height (m)	50
		Power(W)	10567830

Figure 22 - turbine sizing tool results for low and high water flow rates in site 2

Figure 21 and 22 shows the results obtained by using the turbine-sizing tool for low, $10m^3/s$, and high, $30m^3/s$ flow rate of liquid. As for site 1, it has a higher head height; therefore it will be able to produce more energy compared to the pump turbine in site 2. If we assume the maximum discharge rate of water to be $30kg/m^3$, the turbine in site 1 would be able to produce about 14.8MW whereas the turbine in site 2 would be able to produce about 10.6MW. Note that these values are produced by only one turbine being installed in the site. It is usual to have more than one penstock that leads to individual pump turbines. The number of pump hydro turbines to be installed can then be manipulated to give the desired maximum output of the PHS system.

Network status at chosen sites

As the proposed Atlantis project in the Pentland Firth has the potential to generate 398MW, the ability to distribute this energy is dependent on the grid capacity. In the early phases when constructing tidal energy systems in the Pentland Firth, connections can be made to the existing grid by utalising the available 11kV and 33kV networks [23]. However, these networks are limited due to capabilities and location of the grid. As the development of the tidal system progresses, innovative and proactive measures, which include generation and grid management by Renewable Power Zone, which can extend existing grid usability. The Renewable Power Zone uses a combination of different technologies to get more out of the 33kW grid and it increases connectable generation capacity by compelling the generation against thermal capacities of subsea interconnectors to Thurso and between the islands. These developments will lead to extensions and strategic reinforcements of the grid. In due course, larger developments would take advantage of the upgraded grid connectivity and developments in the area, thus further facilitating the transport of energy. The timescale to improve the electricity network will progressively take longer. However, this will ultimately allow more capacity to be accepted by the grid as the renewable energy generation increases in Pentland Firth. The deployment of larger renewable energy systems should be parallel to the upgrades being carried out on the electricity network in order to facilitate the development in the area.

A single 275kV transmission network to Dounreay and a double circuit 132kV line to Thurso then to Dounreay, where they interconnect, connect the north coast of Scotland [23]. Both of these transmission systems originate from Beauly, close to Inverness. This transmission network is essentially the electrical transport system out of the north coast of Scotland, where the Pentland Firth is situated. Figure 23 shows the mainland electricity distribution system.

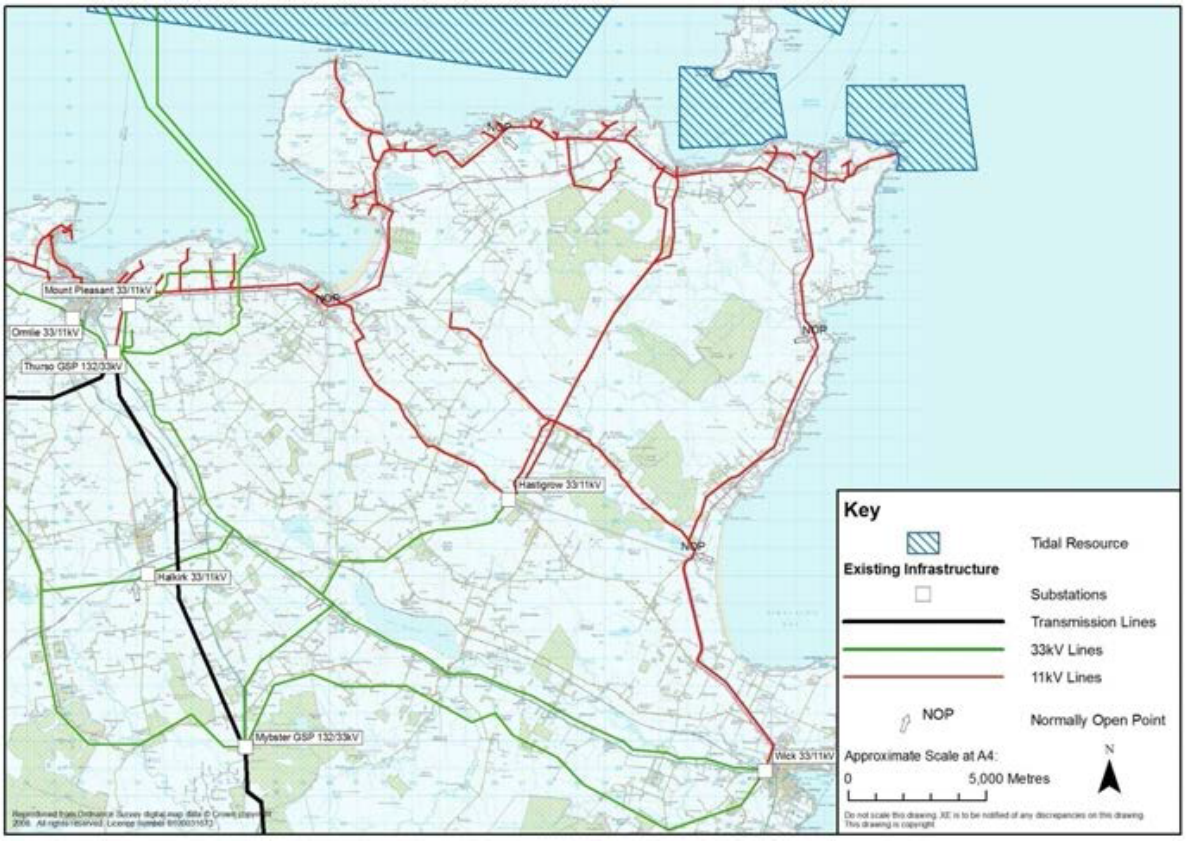

Figure 23 - Mainland electricity distribution system [23]

As it can be seen in figure 23, the transmission lines are far from the available tidal resources along the Pentland Firth.

In Orkney, the grid network is built from a 33kV ring system around the northern isles and two 33kV lines to the southern isles. Two subsea cables from Thurso that are stretched to Scorradale via Hoy supply the 22kV Orkney system. The Orkney grid is running at its full capacity in terms of permissible generation [23]. A Renewable Power Zone has been identified to allow more generation to be connected by means of managing the generation and distribution grid. This is important as the Pentland Firth is to be used to exploit the tidal energy resources capable of generating high volumes of energy.

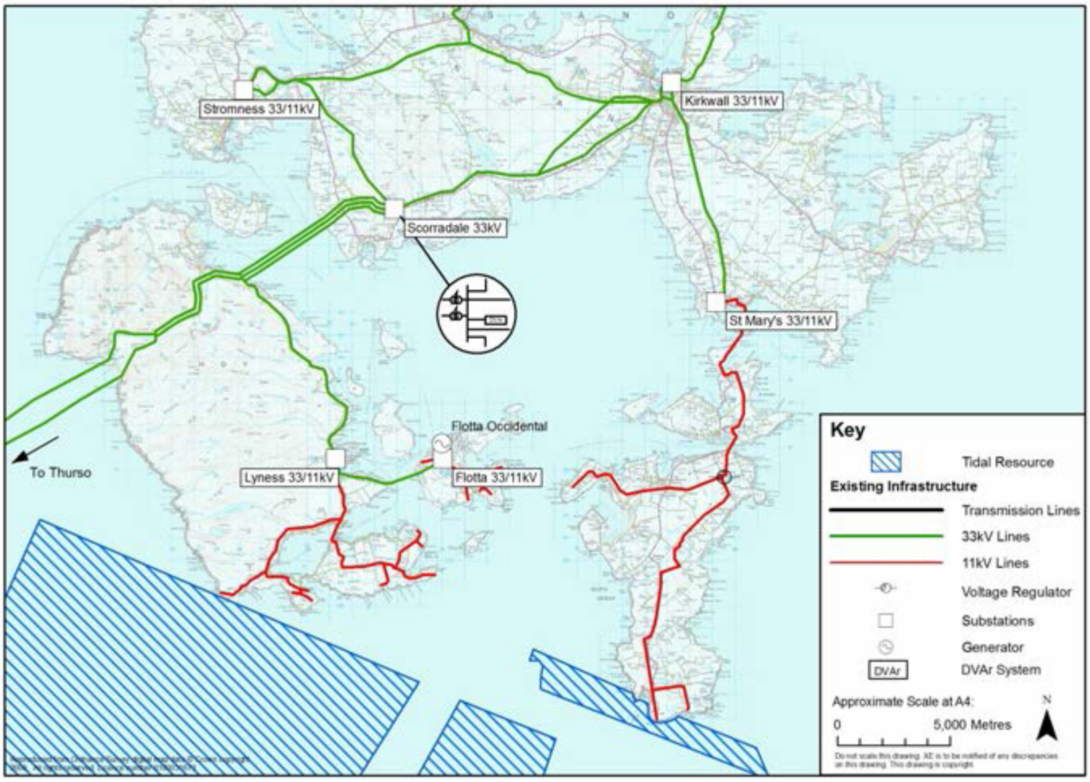

Figure 24 – Orkney distribution system [23]

Figure 24 shows the Orkney distribution system. The 33kV cables from Thurso are passed through voltage regulators and a Dynamic reactive power control system at Scorradale. The circuits of interest with respect to the development plans in the Pentland Firth are one 33kV circuit from Scorradale on Hoy to Lyness, followed by subsea cables to Flotta and another from Kirkwall to St. Mary's primary, thence cables of 11kV down to the southern tip of South Ronaldsay [23]. 0.85MW of wind generation at St. Mary's is already connected in the 11kV network. Hoy and Flotta has a very small primary substation at Lyness and a large substation on Flotta. 2MW of wind generation has already been connected to the 11kV Flotta Primary lines and 10.5MW from Flotta Occident is connected to the 33kV system. The 11kV and 33kV lines are of interest to the tidal developments in the Pentland Firth. However, as mentioned earlier, the capacity for this network is full in regards to generation.

Voltage drop is an issue on the 11kV lines as they span long distances. Available capacities on the mainland range between 100kW and 300kW depending on the point of connection. Near Thurso, there is a possibility of connecting 1MW using the 11kV lines near Murkle Bay. There is no capacity on the 33kV subsea lines from Murkle

Bay to Orkney [23]. As for Orkney, South Ronaldsay has a connectable capacity of around 270kW. Hoy is unable to accept any generation as the lines there are single phase only. South Walls is able to accept up to 200kW.

There are proposals to upgrade the existing capacities of the network in order to allow for more renewable energy generation in the area. Mount Pleasant Substation, close to Thurso can support up to 26MW if its 33kV feeder is upgraded. The grid transformers in Thurso limit the maximum amount of allowed generation and to improve this, the transformer system has to be upgraded. Longer connection routes can be taken from offshore developments to the areas around Thurso and Murkle Bay to allow 26MW to be connected to the grid. This option is suited and can be affordable to large-scale projects. In theory, Orkney capacity can be extendable to 15MW, however this will incur high capital costs to reinforce the 33kV system. Thurso grid supply point has a 26MW export limit, which in turn is the limiting factor for all connections. To upgrade transformers in Thorso, the capital cost is likely to be about £3M and a construction period of two to three years. As there are plans for large-scale deployment of tidal and wave energy systems around Orkney, a grid reinforcement plan has been proposed by the use of an 180MW AC cable connecting Orkney and the mainland [24], the layout of the proposal can be seen in figure 25.

There is a lot of interest to further develop the electricity network in the north coast of Scotland as the area has a lot of potential to deploy renewables not just in the form of tidal stream arrays, by offshore wind turbines and wave energy.

This thesis will assume that there is a transmission network to transfer the energy produced by the tidal array and PHS.

Figure 25 – Layout of proposed 180MW AC cable [25]

Scope of Environmental Impacts

This section will cover the scope of environmental impacts that should be taken into account when deploying a seawater PHS system such as those proposed on site 1 and 2.

Table 8 shows the scope of environmental impacts that should be considered with respect to the site selected.

Environmental impacts to be considered for seawater PHS systems
Disturbances to the habitants of the site (includes humans, animals and plants) during construction and operation of PHS system
Soil compatibility and contamination
Water quality
Disturbances to the natural environment at the input/output of the pump turbine

Table 8 - Environmental impacts to be considered for seawater PHS systems

Besides the scope of environmental impacts in the desired sites, environmental impacts to be considered when setting up a new electricity network framework can be found in table 9.

Environmental impacts to be considered for new network system
Disturbances to inhabitants of desired location of network
Disturbances caused by electromagnetic fields to the environment
If under sea cables are used, topography and soil structure compatibility

Table 9 - Environmental impacts to be considered for new network system

Just as with many other large-scale renewable energy systems, the main disturbances to the environment will occur during the construction phase of the project.

Modeling Energy Captured by proposed Atlantis MeyGen Tidal Energy System

The proposed tidal array set for the Pentland Firth is said to consist of 269 tidal turbines. The tidal turbine assumed to be used in this tidal array could be seen in Figure 26.

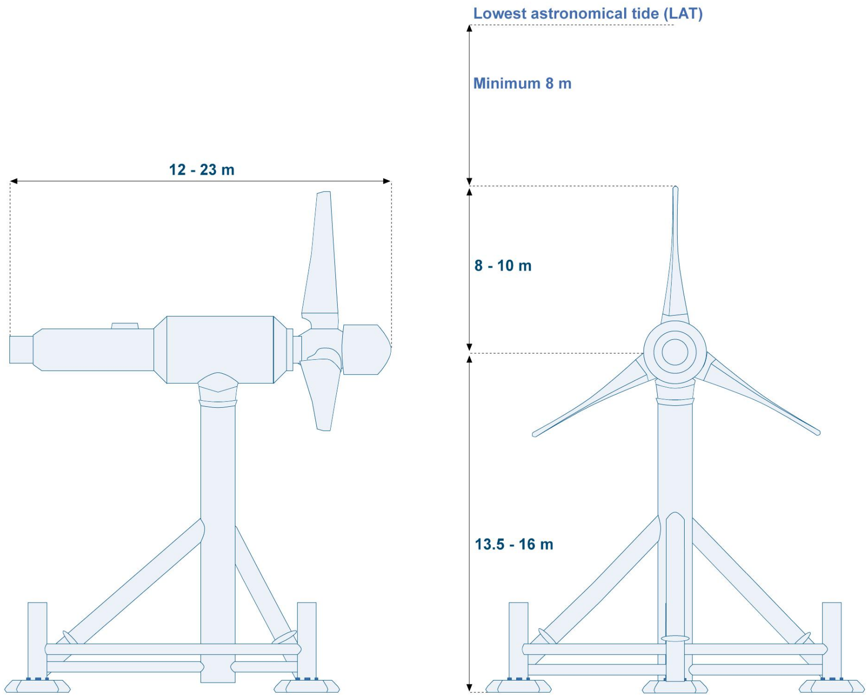

Figure 26 – Tidal stream turbine schematic [26]

To model the 14day tidal cycle of a tidal stream, the following spring and neap tide profiles as seen in figure 27 and figure 28 were used.

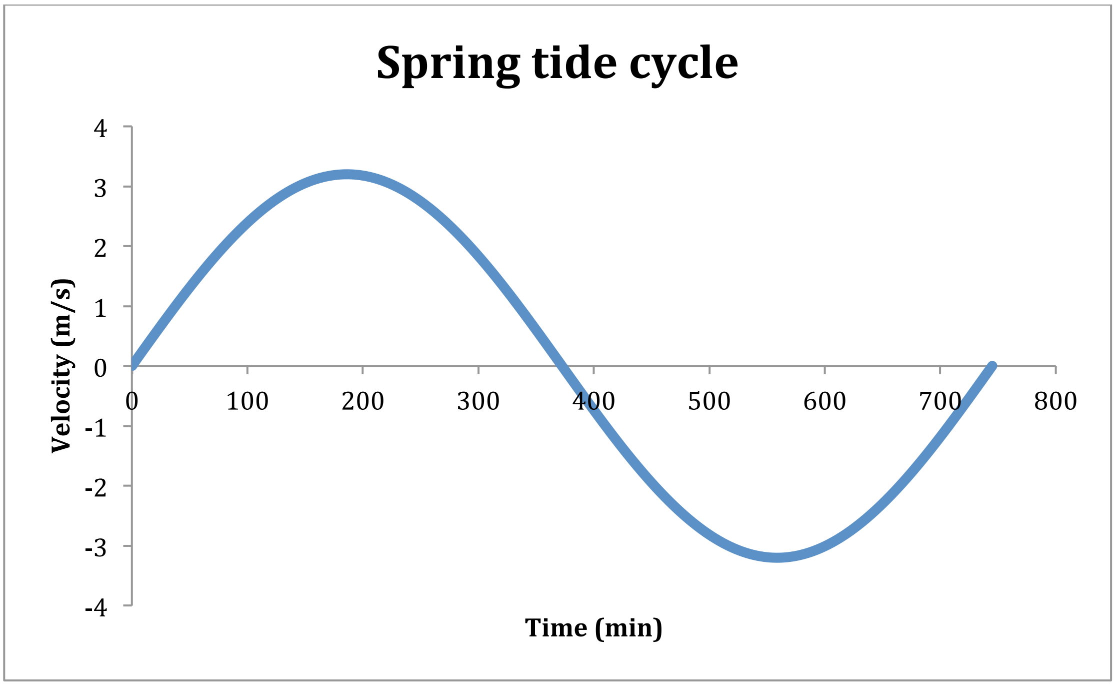

Figure 27 – Spring tide cycle

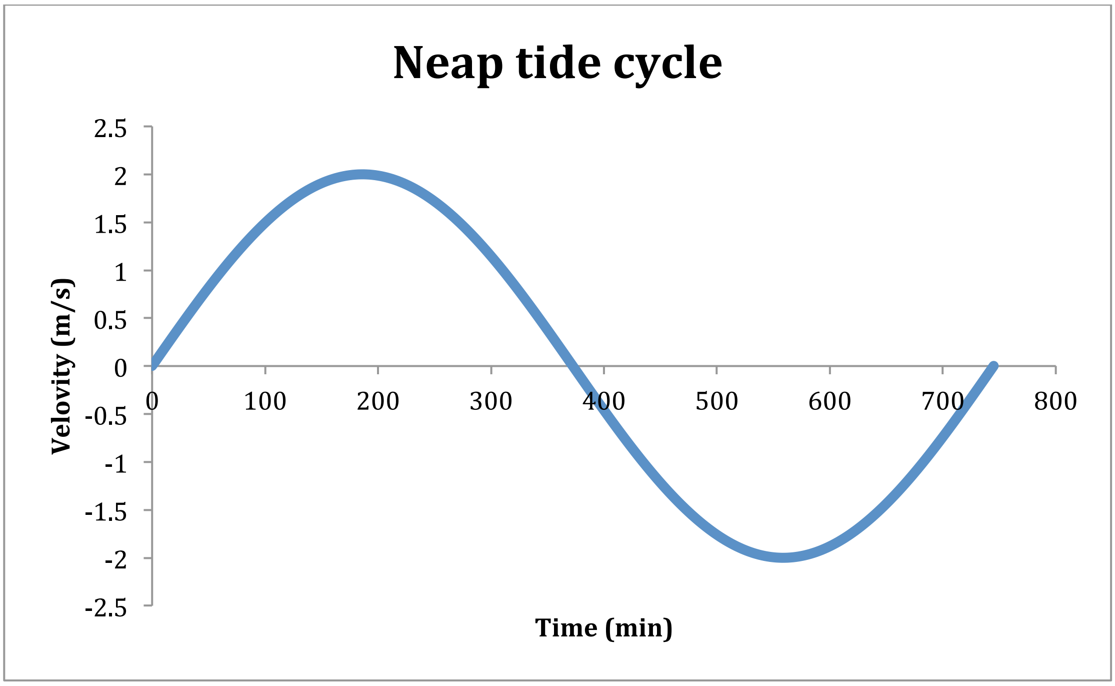

Figure 28 – Neap tide cycle

The spring and neap tide profiles were obtained for a period of 12hours and 25. The maximum velocity for the spring tide was taken to be 3.2m/s and 2m/s for the neap tide. When combining the spring and neap tide profiles, a tidal stream velocity profile over a period of 14days was obtained and can be seen in figure 29 below.

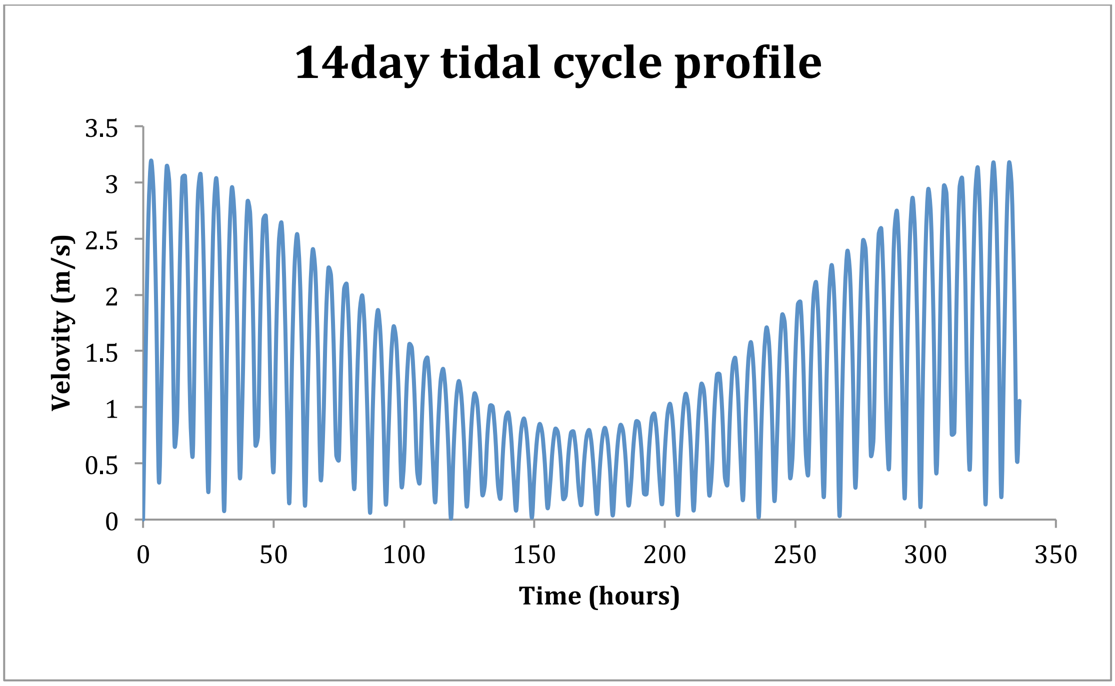

Figure 29 – 14day tidal cycle profile

Taking the spring and neap tidal profiles, the power available from these tidal profiles were extracted and can be seen in figure 30 and 31.

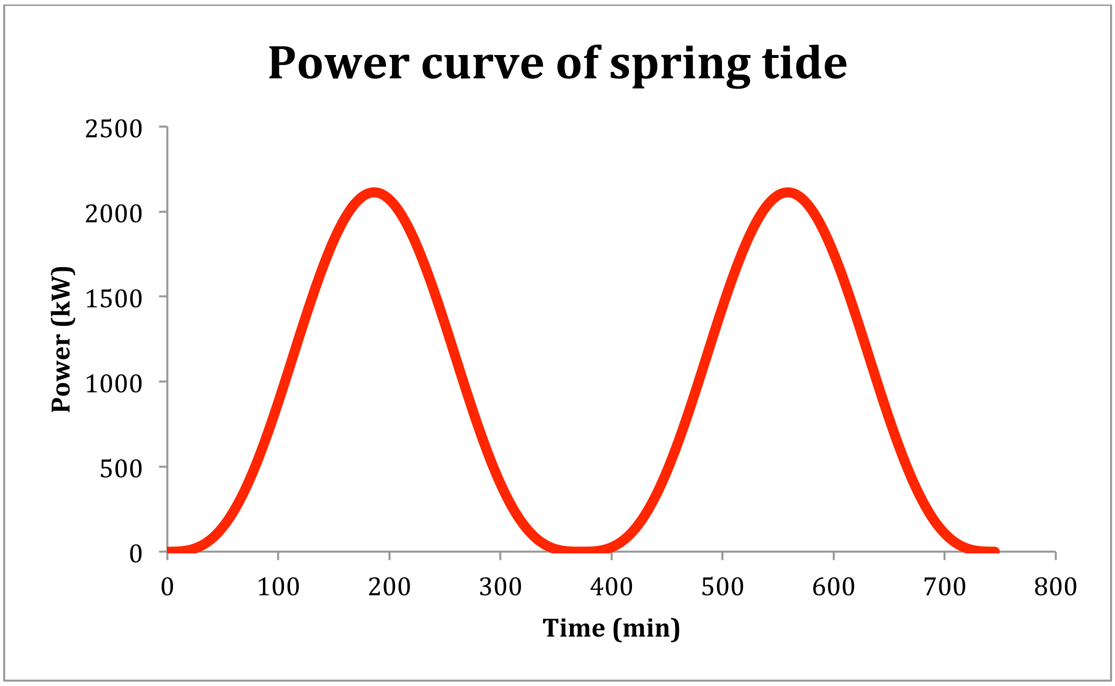

Figure 30 – Power curve of spring tide

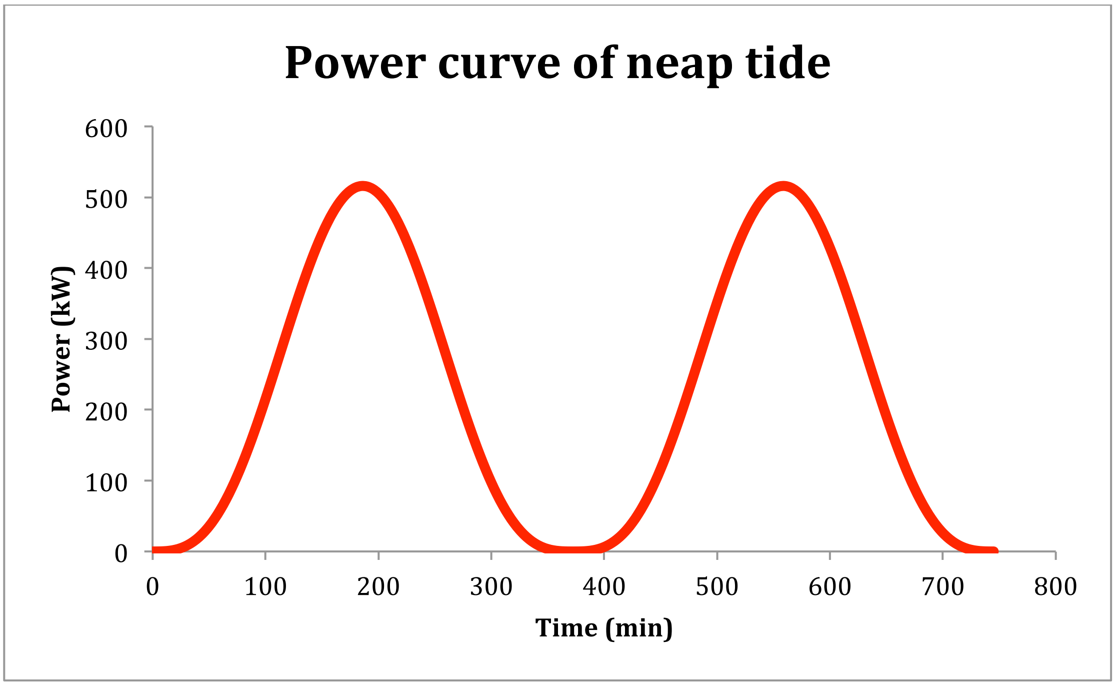

Figure 31 – Power curve of neap tide

The peak of the power curve during spring tide was found to be about 2.1MW whereas the peak of the power curve during neap tide is about 0.5MW. As expected, the power available from the spring tide is larger compared to the power available from the neap tide. Using the power curves obtained from the respective tidal stream, the power that a tidal stream turbine can extract can then be calculated. Equation 5 represents the turbine power output.

$$Tidal\ turbine\ power\ output(W) = \frac{1}{2} \times \rho \times A \times V^3 \times C_p \quad (5)$$

Where ρ (kg/m^3) is density, A (m^2) is the swept area of the turbine blades, V (m/s) is the velocity of the tide and C_p (%) is the turbine power coefficient.

By using equation 5, the tidal turbine output for 1 tidal turbine was obtained. The density is taken to be 1027kg/m^3, swept area of turbine blades is taken to be 314m^2, which was obtained from the turbine specifications in figure 26, and the power coefficient is 40%. As for the turbine specifications, the cut in velocity is taken to be 1m/s and the rated velocity is taken to be 3m/s. With all these values, the tidal turbine output for 1 turbine for the 14day tidal cycle can be seen in figure 32.

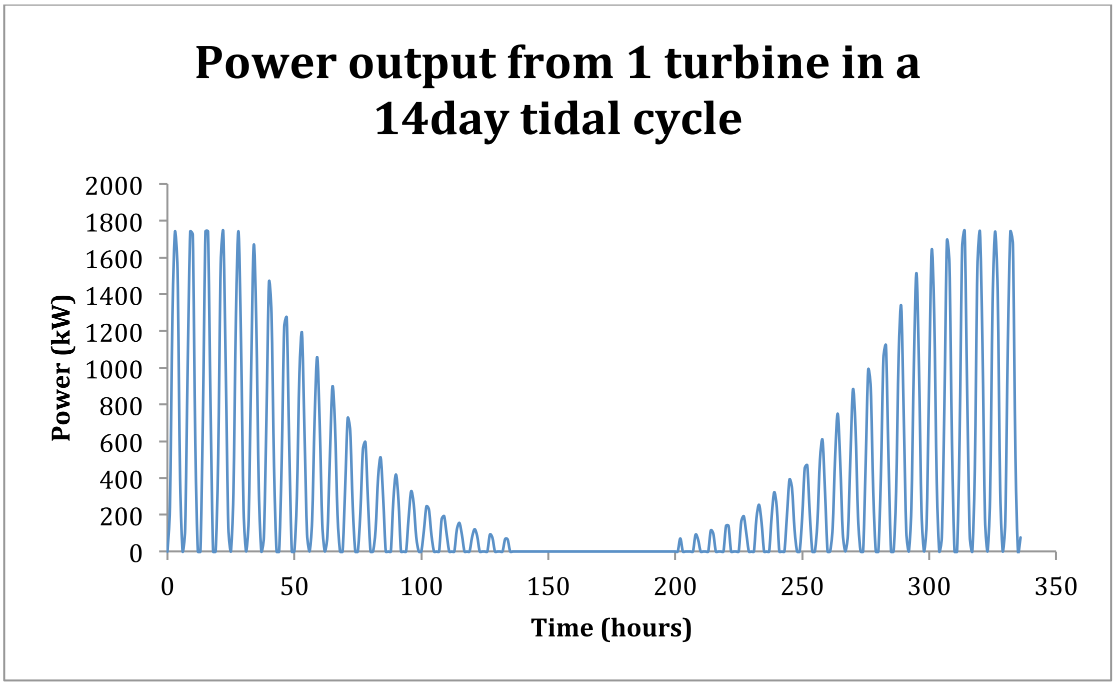

Figure 32 – Power output from 1 tidal turbine for the 14day tidal cycle used

By summing the area under the graph, the amount of energy 1 tidal turbine can produce in the 14day tidal cycle profile can be found. The total energy produced was calculated to be about 108MWh. Assuming the 14day tidal cycle profile remains the same throughout the year, the annual output from 1 tidal turbine is about 2.82GWh. The proposed tidal array is said to consist of 269 tidal turbines. Assuming all the turbines used in the array have the same specifications used in this modeling and the tidal profile remains the same throughout the year, the proposed tidal array can produce about 759GWh annually.

If a PHS were to be used to create a base load from the tidal array, figure 33 below illustrates the mean power output from 1 tidal turbine during the 14day tidal cycle.

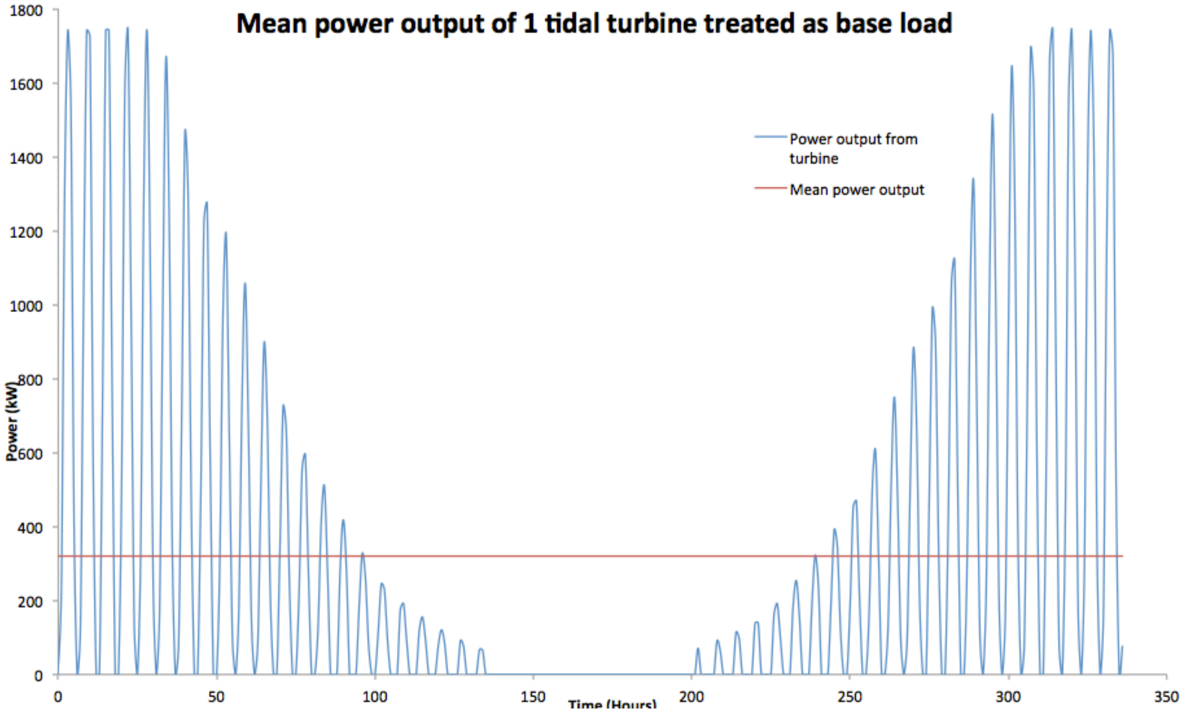

Figure 33 – Mean output from 1 tidal turbine if treated as base load

The power curves during spring and neap tides can be seen in figure 34 and 35.

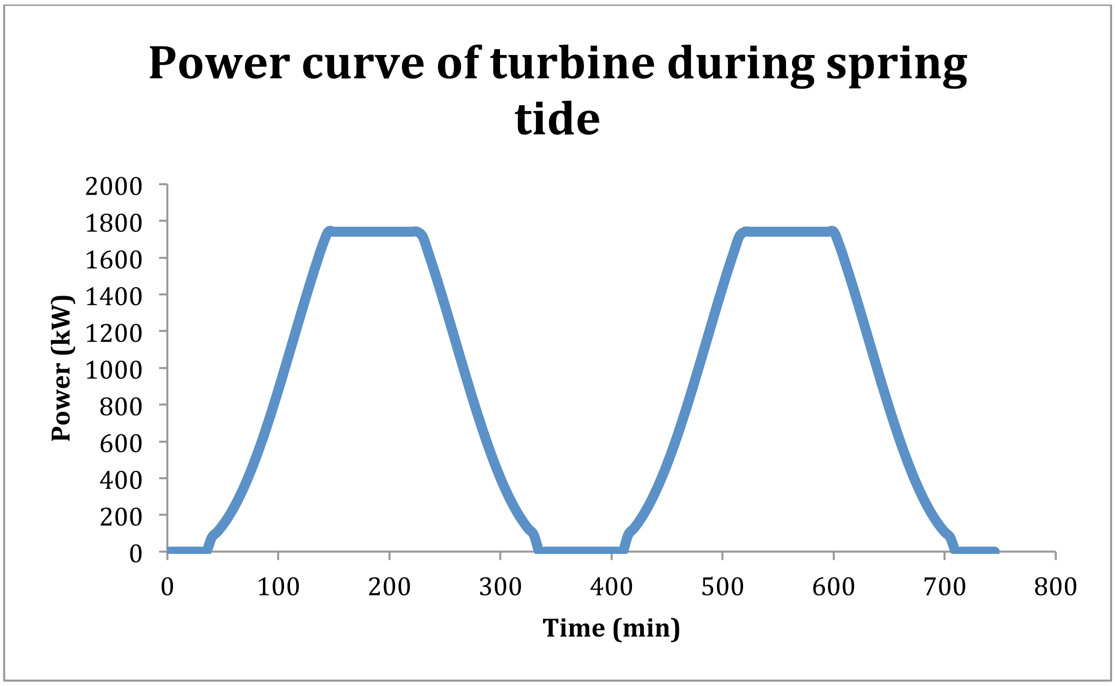

Figure 34 – Power obtained from 1 tidal turbine during spring tides

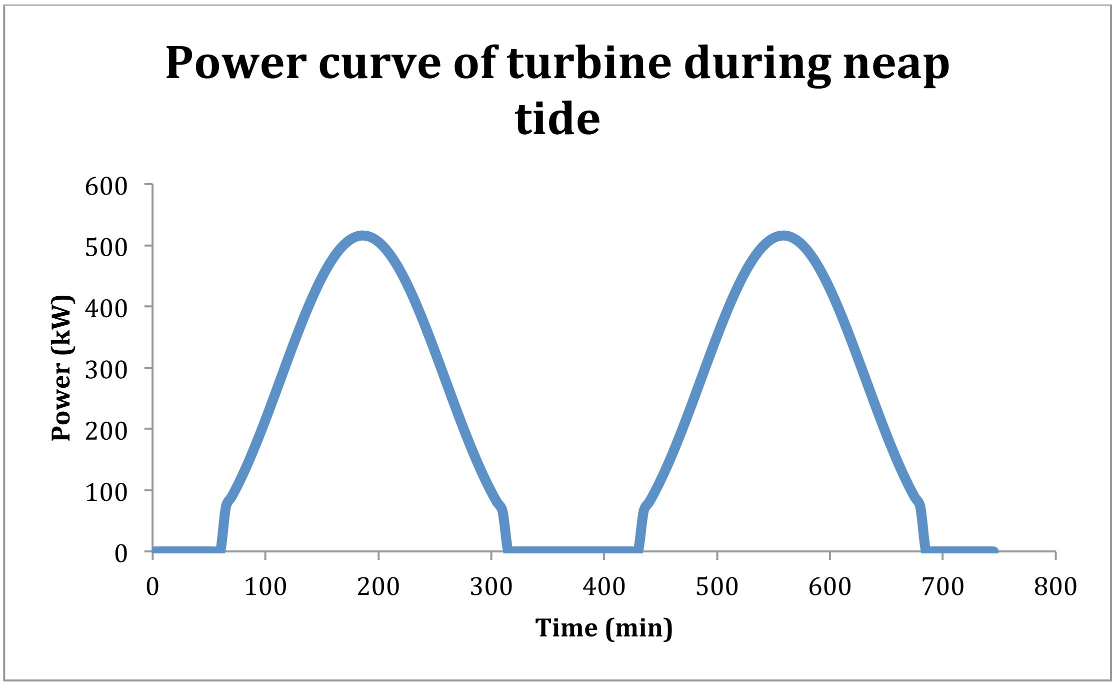

Figure 35 – Power obtained from 1 tidal turbine during spring tides

As seen in figure 34, the peaks of the power curve flatten. This is because the tidal turbine specified has reached its rated power output, which is about 1.7MW. This is further illustrated in figure 36 below where the power curve for the spring tide and power curve of the turbine is plot on the same graph.

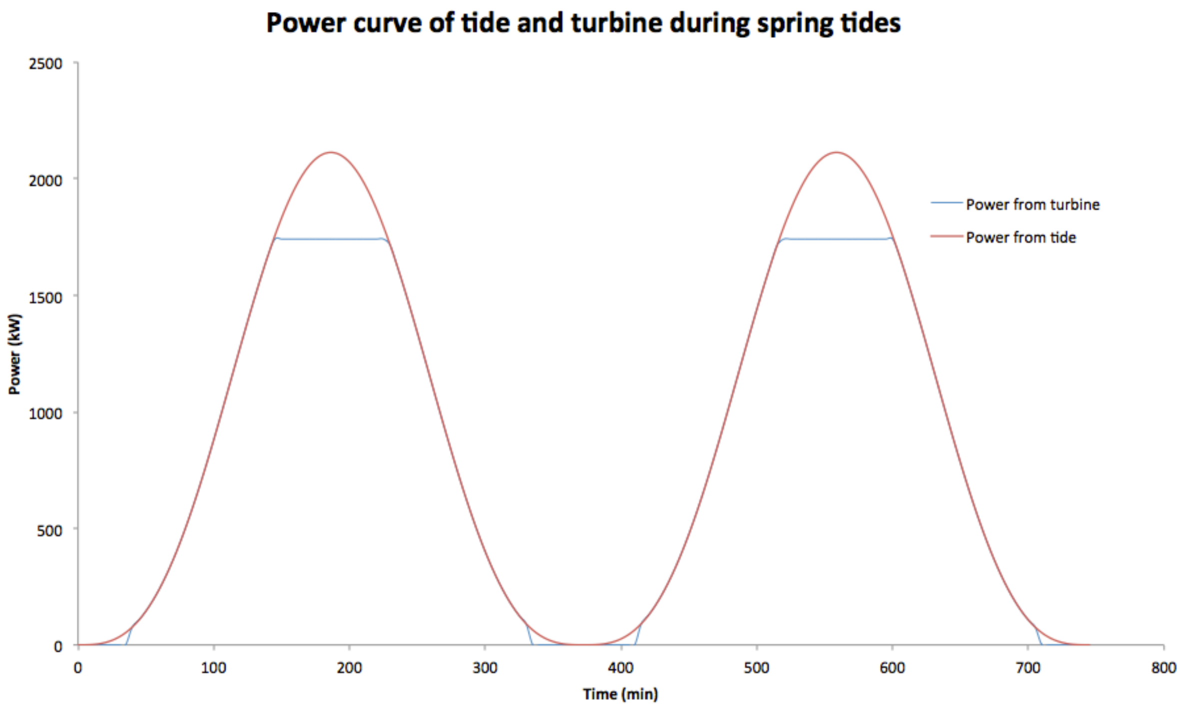

Figure 36 – Power curve of tide and turbine during spring tides

As seen in figure 36, there is a period in the tidal cycle where very little to no power is available between 300th and 450th minutes. A PHS will be used to allow the tidal turbine to generate a base load power profile. In order to do so, the mean power was calculated and found to be about 840kW. This is illustrated in figure 37.

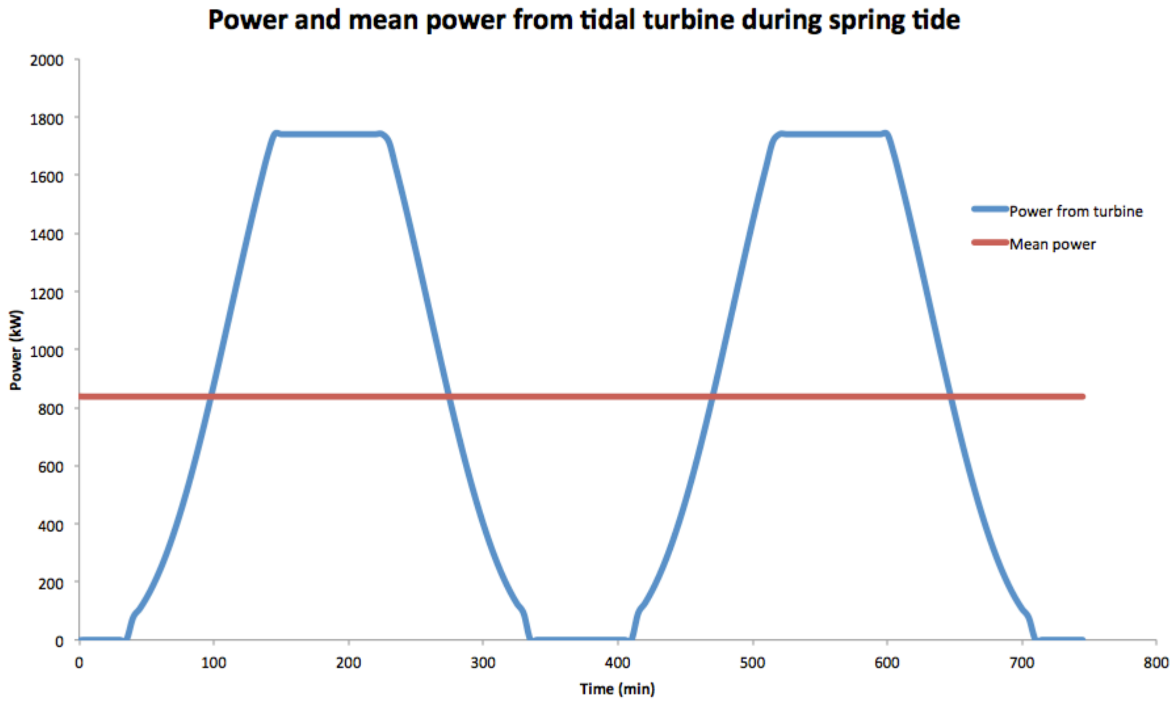

Figure 37 – Power and mean power from tidal turbine during spring tide

To get a power profile that is flat, the energy produced by the tidal turbine in the first half of the tidal cycle, above the mean power, will be stored in the PHS system to fill the low energy gap between the first half and the second half of the tidal cycle.

From calculations carried out, it was found that in 1 full spring tidal cycle, the energy produced by 1 tidal turbine is about 624MWh. Therefore in half a cycle 312MWHh is produced. The energy below the mean power line for 1 full tidal cycle was found to be 386MWh; meaning in half a tidal cycle the energy is taken to be 193MWh. This indicates that the excess energy available to be stored is 119MWh for 1 tidal turbine.

The same method was used to calculate the excess energy to be stored in order to achieve a base load profile for the neap tidal cycle. It was found that the excess energy to be stored for the neap tidal cycle is 32.5MWh for 1 tidal turbine.

An investigation was carried out for the 269 tidal array proposed for the Pentland Firth. Assuming the conditions are the same for the entire area of the tidal array, and all tidal turbines used in the array has the same specifications, the excess energy from a tidal array of 269 tidal turbines during peak spring tides was found to be about 32GWh and about 8.7GWh during neap times. By using a PHS that has a round trip efficiency of 70%, the energy generated by this PHS to achieve a base load profile was found to be 22.4GWh during spring tides and 6.1GWh during neap tides.

By using these values, a 14day tidal cycle for the energy stored by the PHS per cycle for the 269 tidal turbine array was produced and can be seen in figure 38.

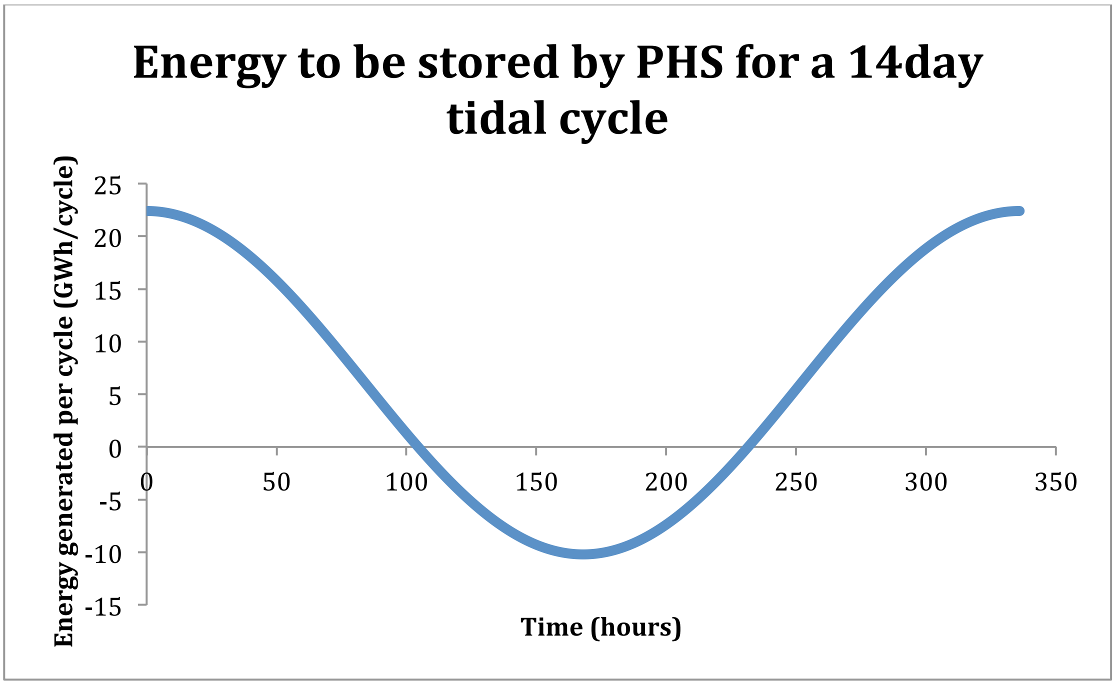

Figure 38 – Energy to be stored by PHS per cycle over time for a 14day tidal cycle

Figure 38 shows the energy stored by the PHS per cycle for the spring and neap tides in a 14day tidal cycle. It can be seen in figure 38 that the energy in the PHS during this 14day tidal cycle is more than the energy required to achieve a base load profile. The total energy stored in the PHS for this 14day tidal cycle was found to be 2.9TWh and the energy required to be produced by the PHS to obtain a base load profile was found to be 842MWh. This indicates that in a 14day tidal cycle, there is an excess energy of about 2.06TWh.

The output from the PHS can be manipulated in order to get the desired base load output. This is illustrated in figure 39 below.

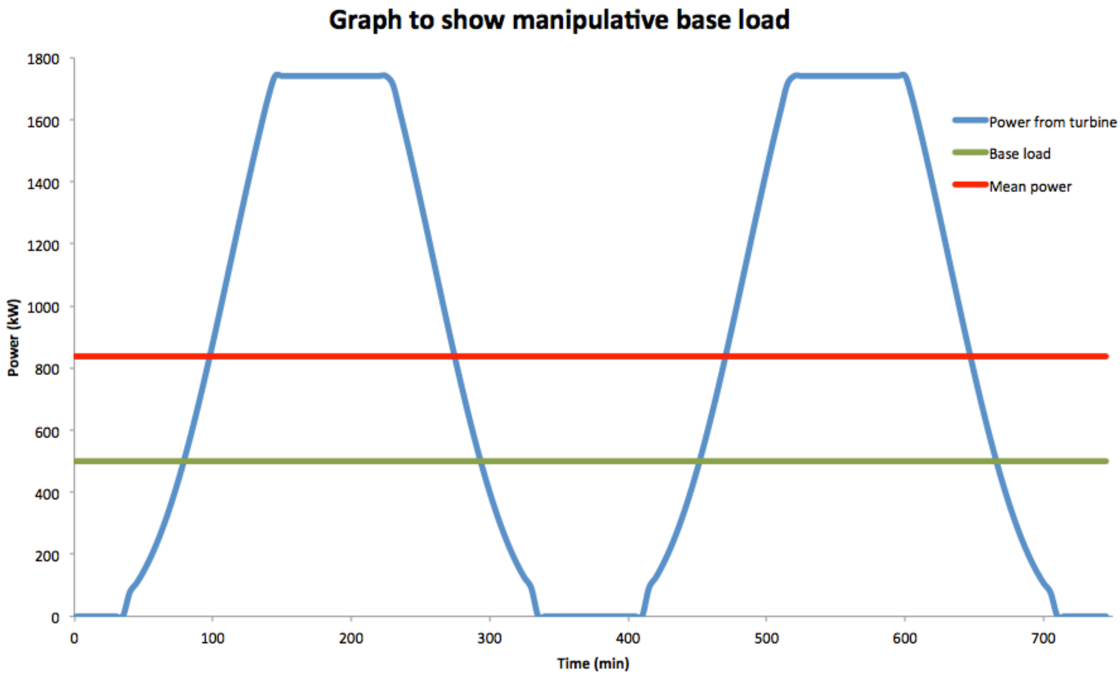

Figure – 39 Graph to show manipulative base load

Figure 39 shows the power generated by 1 tidal turbine. The base load can be manipulated to any power below the mean power output. When lowering the base load output of the turbine, the area above the chosen base load will be larger than the area required to fill the gap between the two power peaks generated from the turbine. This indicates that there is excess energy in the PHS if setting the base load below the mean power output. This is desirable when there is a sudden need for energy, the energy can then be extracted from the PHS to facilitate the sudden rise in demand. It can be concluded that the higher the output of the tidal array, the higher the base load. However, to facilitate this, the size of the PHS has to be increased. A study on the size of the PHS required for the proposed tidal array can be seen in the next section.

PHS required for proposed tidal array

To model the energy going in and out of the PHS facility, the excess energy generated by the tidal array will be used to pump water into the PHS facility as a means of storing energy. The round trip efficiency of the PHS is taken to be 70%. At times when the tidal array is not generating electricity, power will then be extracted from the PHS to achieve a base load power profile.

Using this specification for the PHS, the capacity of the storage required to achieve a peak base load energy generation profile was found to be 22.4GWh, given that the peak generation of the tidal array is 32GWh. 22.4GWh is taken to be the maxium storage capacity of the PHS in order to achieve a base load profile for the 269 tidal array.

The storage capacity of the Cruachan PHS scheme was calculated using the PHS tool to investigate the size of PHS needed by the proposed tidal array. The results can be seen in figure 39.

To calculate the storage capacity of a pumphydro system, we need to find the following:
1) Volume of reservoir
2) Mass of liquid in reservoir
3) Potential energy of the fluid in a reservoir at a given height

VOLUME OF RESERVOIR
Equation for a container with linear sides, Volume = Length x Breadth X Height

Length (m)	0
Breadth (m)	0
Height (m)	0
Volume (m^3)	0

MASS OF LIQUID IN RESERVOIR
Mass = Volume x Density

Volume (m^3)	10000000
Density (kg/m^3)	1000
Mass (kg)	10000000000

POTENTIAL ENERGY STORED IN RESERVOIR
Potential Energy = Mass of Liquid in Reservoir x Gravitational Acceleration x Head Height

Mass (kg)	10000000000
G. Acceleration (m/s^2)	9.8
Head Height (m)	396
Potential energy (J)	3.8808E+13

As potential energy is in Joules, we have to convert it to kWh
1 Joule is equivalent to 0.000000278 kWh

Energy (J)	3.8808E+13
Power (kWh)	10788624

Figure 40 – Cruachan storage capacity using PHS tool

As it can be seen in figure 39, the storage capacity of Cruachan was found to be about 10.8GWh when using the PHS tool. Therefore for the tidal array proposed, the deployment of about 2.07 Cruachan power stations has to be installed.

The proposed site 1 has a storage capacity of 164MWh and as for site 2 a capacity of 870MWh. As the storage capacity of a PHS scheme to be used for the proposed 269 tidal turbines requires a storage capacity of 22.4GWh to achieve a base load profile, both the PHS on site 1 and 2 are unable to meet this criterion.

The main benefit of having a base load power system integrated to a PHS is that the minimum power available is known over a period of 24 hours, therefore variations in demand can be met instantaneously. A base load profile is suitable to sites where the electrical demand is constant such as industrial zones and data centers. If this integrated tidal and PHS scheme is coupled to a known demand profile, the scheme can take the area off the national grid, thus making the area autonomous. This is a major advantage as there are areas in the Orkney region where there is limited connectivity to the national grid. Transmission lines can be placed in order to make these communities autonomous.

Conclusion and Future Work

This thesis has shown that it is possible to use a pump hydro storage as a means to create a base load profile for a tidal array due to the predictable nature of the tidal stream resource. However, to prove this a practical experiment should be conducted. The scale of the array studied is large; a study on a small tidal array integrated with a suitable sized pump hydro storage should be conducted to test the findings in this thesis.

Future work that can be conducted following this thesis could be a cost analysis of the entire system. This includes the cost of the tidal array, cost of the pump hydro storage and the costs to connect the systems to the grid. Further cost studies may include the cost of upgrading the electricity network to facilitate the growth of renewable generation in the area. The cost analysis can investigate the cost effectiveness of the systems.

Other future work includes investigating the capacity of the network system already in place around the Pentland Firth, in order to work out how much capacity can be added to the network that would come from the tidal array and the pump hydro storage.

References

[1] Wagner H-J., Mathur J., 2011. Introduction to Hydro Energy Systems. Springer.

[2] National Hydropower Association. Hydro Works For America.

[3] DOE Energy Storage Database. Herdecke Pumped Storage Power Plant. Sandia National Laboratories.

[4] Competence Guide. Pump-Storage Power Plant Herdecke. http://www.energystate.de/detail.php?lang=en&kat=project&id=200 [Accessed 27th July, 2014]

[5] Eclipsol Energy Inc. Technology. http://www.eclipsol.com/about-4-1/ [Accessed 29th July, 2014]

[6] http://www.fhc.co.uk/pumped_storage.htm [Accessed 29th July, 2014]

[7] Ter-Gazarian A. G., 2011. Energy Storage for Power Systems 2nd Edition. The institution of Engineering and Technology.

[8] http://www.visitcruachan.co.uk/about/history.asp [Accessed 2nd August, 2014]

[9] Cruachan Power Station Site Information. Scottishpower Energy Wholesale. Issue 01/2010

[10] BBC News. Engineering award for Cruachan Power station's 'hidden' hydro scheme. http://www.bbc.co.uk/news/uk-scotland-glasgow-west-20562195 [Accessed 2nd August, 2014]

[11] http://www.esru.strath.ac.uk/EandE/Web_sites/03-04/wind/content/storage%20available.html [Accessed 4th August, 2014]

[12] IEA Hydropower Implementing Agreement Annex VIII. New Energy Foundation, Japan, 2006.

[13] Fujihara T., Imano H., Oshima K., 1998. Development of Pump Turbine for Seawater Pumped-Storage Power Plant. Hitachi Review Vol. 47.

[14] Charlier R. H., Finkl C. W., 2009. Ocean Energy: Tide and Tidal Power. Springer.

[15] BBC News, 2014. Tidal energy project to be constructed in the Pentland Firth. http://www.bbc.co.uk/news/uk-scotland-28887542 [Accessed 26th September, 2014]

[16] Hardisty J., 2011. The Tidal Stream Power Curve: A Case Study. Energy and Power Engineering.

[17] 2013. Wave and Tidal Energy in the UK: Conquering Challenges, Generating Growth. renewableUK.

[18] 2008. Atlas of UK Marine Renewable Energy Resources: A Strategic Environmental Assessment Report. ABPmer, The Met Office, Proudman Oceanographic Laboratory.

[19] BBC News, 2014. Tidal energy: Pentland Firth ‘could power half of Scotland’. http://www.bbc.com/news/uk-scotland-north-east-orkney-shetland-25800448 [Accessed 26th September, 2014]

[20] http://www.meygen.com/the-project/pentland-firth-inner-sound/ [Accessed 15th September, 2014]

[21] BVG Associates, 2011. Wave and tidal energy in the Pentland Firth and Orkney waters: how the projects could be built. The Crown Estate.

[22] Chen H., Cong T. N., Yang W., Tan C., Li Y., Ding Y., 2008. Progress in electrical energy storage system: A critical review. Elsevier.

[23] Scott N. C., Smeed M. R., McLaren A. C., 2009. Pentland Firth Tidal Project Grid Options Study. Xero Energy.

[24] Snodin H., 2014. Scottish Islands Renewable Project: Grid Access Study. Xero Energy.

[25] Connecting Orkney: Electricity Network Reinforcement. Scottish and Southern Energy.

[26] http://www.meygen.com/technology/ [Accessed 1st August, 2014]