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Stromeferry Tidal Generation Report

Feasibility Study

October 6th 2013

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Prepared for:
The Highland Council

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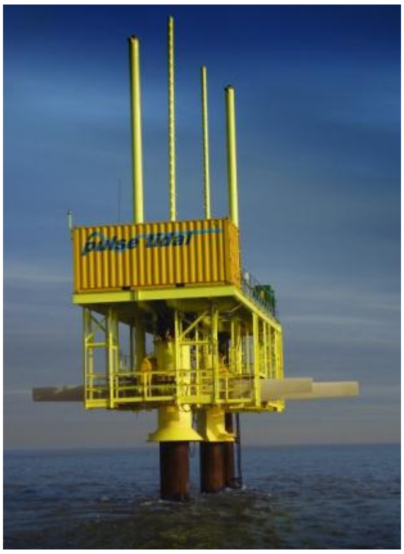

REVISION SCHEDULE

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1	09/10/2013	First Draft	Josh Sherratt Principle Engineer	Graeme Cook Associate Project Manager	[Name] [Position]
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1 EXECUTIVE SUMMARY

The following report discusses possible tidal generation options which could be applied within the Strome Narrows of Loch Carron in conjunction with the construction of a bridge or tunnel in the area.

The report builds on the preliminary studies undertaken as part of the Stage 1 feasibility study and the conclusions made within the Stage 1 Report. This report considers further the application of the tidal technologies that were identified, how they would operate under local tidal conditions, the practicalities of their implementation and operation and the associated costs.

Stromeferry is located in the north west of Scotland at the head of Loch Carron. The village is accessible by a local road system which is regularly disrupted by natural events, some of which have left the village isolated for prolonged periods. The village falls within the remit of The Highland Council who has recognised the negative impact of these disruptions.

As such The Highland Council has requested URS to undertake an investigation into possible options to improve the roads network in the area. These studies have resulted in a number of alternative road upgrade options as shown in Appendix A, including the construction of a bridge or tunnel to cross the Strome Narrows which is the shortest section of the loch. These preliminary investigations concluded that of the solutions, the tunnel and bridge were more expensive when compared to alternatives. However as the area is considered to have significant tidal resource a further investigation to review tidal generation as part of the solution to offset costs was undertaken.

Focusing on three tidal technologies the Tidal Barrage, Tidal Stream Device and Tidal Fence, URS have considered the practical feasibility of each of the options and the benefits they could bring.

A Tidal Barrage would require the construction of a barrage or dam across the narrows with generators located within the structure. The tide is allowed to enter the enclosed (dammed) area through sluice gates. Once filled, the gates are then closed and the water contained. This forms a head between the receding tide and the contained water which can then be used to generate electricity in a similar fashion to a hydroelectricity plant. There are a number of tidal barrages currently in operation throughout the world however as they require a considerably greater level of civil engineering in comparison to the other tidal technologies and present a significant risk to the Loch Carron environment, hence URS would not recommend the application of Tidal Barrage technology at this location without mitigation of these risks.

Tidal Stream Devices (TSD) operate in a similar fashion to wind turbines. They would be located in the tidal stream of the Narrows which would allow them to generate electricity. TSD technology could potentially have a lower impact on the environment than the Barrage solution however the low flow rates (1.5m/s) and the shallow depth of the narrows (16m deepest section) limits the achievable level of generation and thus their economic feasibility.

The application of Tidal Fence technology proposes to reduce the width of the narrows thereby increasing the flow and presenting greater generation opportunities. This technology offers the most attractive of the three options however it is still in its infancy and would require a substantial level of capital investment and is subject to the inherent risk from both. As the technology develops and more data becomes available it will become clearer as to the suitability of this technology. It is therefore recommended that further studies be carried out as the project develops.

Following the study it has been identified that under the constraints of the current market conditions both Tidal Fence and Tidal Barrage Technologies would provide financially returns sufficient to cover their capital, operational and maintenance costs and only the Tidal Barrage at sufficient levels to justify its inclusion in the roads scheme.

This report has considered the current electricity price and financial benefits at today's levels however if there were to be considerable favourable changes in the electricity market or government regulations prior to the commencement of the road scheme then either the TSD or Tidal Fence options should be reconsidered.

2 INTRODUCTION

The purpose of this study is to determine the technical feasibility and financial benefits of a number of concepts aimed at:

- Taking advantage of the need to improve the road infrastructure in the Loch Carron area.
- Capitalising on the opportunity to integrate a tidal energy project to generate revenues that may offset the road schemes costs.

This report builds on the preliminary studies undertaken as part of the Stage 1 feasibility study and the conclusions made within the Stage 1 Report. This report considers further the application of the tidal technologies identified, how they would operate under local tidal conditions, the practicalities of their implementation and operation and their associated costs.

Three technologies have been reviewed to assess their feasibility. It must be noted that a considerable number of assumptions have been applied throughout this report to allow for a high level assessment to be completed. URS recognises these and advises that any option to be progressed will need to be subject to a further detailed assessment.

The three technologies that have been reviewed are:

- A tidal barrage whereby advantage is made of the tidal range to generate power, with the available energy a function of both the tidal range and the volume of water impounded. Tidal barrages require major civil works and have a significant capital cost and considerably impact to the environment.
- A tidal stream device (TSD) whereby advantage is made of the tidal velocity in the stream (tidal flow). Energy generation is determined by the tidal velocity and the size of tidal device. Unlike a barrage where much of the water is arranged to flow past the turbine, TSDs only utilise the proportion of energy which is within turbine collection area. TSDs require less capital outlay and a reduced level of civil works.
- A tidal fence is arranged to restrict the flow rates to travel through a reduced flow area, forcing the local tidal velocity to increase. This higher velocity increases the available energy for generation. Tidal Fence technology is still developing with no commercial technologies currently in operation at the time of writing.

3 DETAILS OF PROJECT

3.1 History

Stromeferry's location makes access to the village prone to natural events which have in the past cut off all access for prolonged periods of time. Following the most recent land slip The Highland Council requested URS to undertake a study of possible road upgrades that would provide a more permanent access solution to the area.

The study resulted in a number of options (see Appendix A) one of which considers crossing the Strome Narrows with a bridge or tunnel. The cost of this option is considered high when compared to alternative routes however the geographic location of the loch presents opportunities to incorporate tidal generation to offset the cost of the crossing.

3.2 Location

Stromeferry is located near the head of a sea loch, Loch Carron, along the northwest coast of Scotland. The area falls within the boundaries of The Highland Council and contains a number of small villages which predominantly surround the loch. Tourism is an important contributor to the local economy and is the main form of employment.

The loch enters the sea through a narrows approximately 330m wide at its narrowest point which can achieve tidal flows of up to 3knots (1.5m/s).

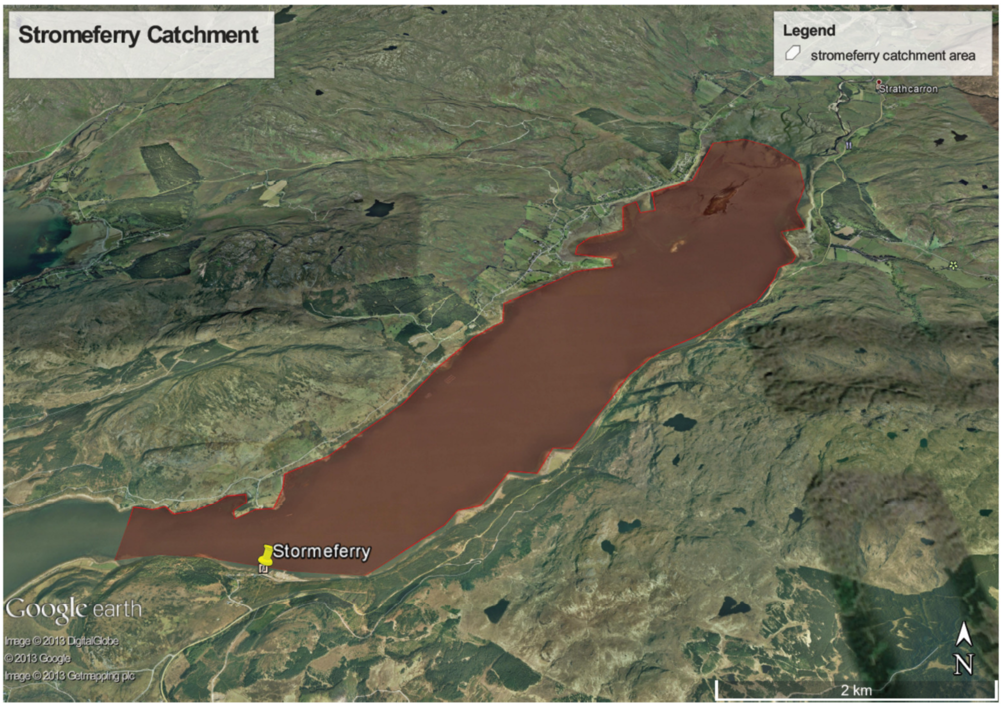

Figure 1 Location of Stromeferry and Loch Carron

4 TIDAL RESOURCE AND AVAILABLE ENERGY

4.1.1 *Tidal Resource*

Tidal energy generation is still considered a developing renewable technology however it offers a number of technical advantages over other renewable energy sources.

Tidal activity is based on the location and alignment of the sun and the moon and it can therefore be predicted giving the supplied utility the opportunity to plan and forecast future energy production. Tidal cycles follow the following patterns:

- Tides flow in and out of estuaries and rivers on a regular cycle (approximately 12 hours 25 minutes, 2 tides every 24 hours and 50 minutes.
- Spring (largest) tide every 2 weeks – new moon and full moon (where the earth, moon and sun are in alignment with each other).
- Neap (smallest) tide every other 2 weeks – moon at quarter phase.
- Remaining tides are 100% predictable.

4.1.2 *Tidal Energy*

The tidal energy available throughout the month reflects the cycles of the moon and the sun. To determine the tidal energy URS has run a high level model of the area and produced the following estimated tidal ranges which have subsequently been used for the preliminary energy calculations (see Appendix B for calculation details).

Tidal energy comprises of two forms of energy:

Potential energy

Potential energy is related to the difference of position of an object in space. In the case of tidal generation this is the height between water levels.

As a base-line, a maximum preliminary potential energy calculation has been taken. This has considered the size of the loch and the volume of water. Although this will not give an indication of the final installed generation capacity it does provide an upper limit and a normalised value.

The following calculation gives the total potential tidal energy of Loch Carron:

$$E_p = 0.5\rho g A_b \triangle h_b^2$$

$E_{p=}$ Potential Energy

ρ= Density of sea water (1025 kg/m^3)

g= Acceleration due to gravity (9.807m/s$^{2)}$

A_b= Horizontal area of the enclosed basin (m^2)

$\triangle h_b$= Mean tidal range in the basin (m)

The factor 0.5 accounts for the reduction in hydraulic head across the barrage as the impounded water empties.

Table 1 shows estimates of the possible potential energy available during each of the lunar tides. The tide heights are shown as heights above the chart datum.

The Mean Sea Level (MSL) of Loch Carron has been estimated at 3.53m.

The maximum total power over a 14 day tidal cycle based on a linear change in tides from Spring to Neap tide heights is estimated at 6202MWh per 14 day cycle based on diurnal tide cycle and a total yearly generation of 86825MWh/year

Table 1 Available Potential Energy

Tidal Cycle	High Tide (m)	Low Tide (m)	Difference in Tidal Heights (m)	Maximum Generation Capacity (kW/day)	Equivalent daily energy available[1] (MWh)
Mean High/Low Water Spring Tides	5.7	0.9	4.8	34,580	830
Mean High/Low Water Neap Tides	4.4	2.6	1.8	4,860	117

Kinetic Energy

Kinetic Energy is related to the speed of the tidal stream and is the energy that the tidal stream and tidal fence devices could potentially harness. To harness the energy TSD as discussed in Section 6 and 7 will need to be installed. These operate in a similar fashion to wind turbines and as such only transfer the energy that interacts with the blades leaving the remaining stream un-used and reducing the overall energy available to be converted.

The available Kinetic Energy can be calculated from the following equation. This provides an indication of the maximum possible Kinetic Energy available by harnessing the loch's tidal stream however practical limitations would reduce this considerably as discussed in Sections 0 and 7 of this report.

The total Kinetic Energy for Loch Carron can be calculated as follows:

$P_k = ½ \rho AV^3$

ρ= Density of sea water ($1025kg/m^3$)

A = The swept area of the turbine rotor. As no turbine has been identified at this stage an assumed area of $78.5m^2$ based on a maximum rotor diameter of 10m placed in 20m of water with 5m clearance to the seabed and surface has been applied.

V= The undisturbed stream velocity. This has been assumed at 1.5m/s based on stream velocities identified within Admiralty charts and does not consider the variations of velocities across tidal ranges.

Table 2 Maximum Potential Available Power

	Velocity 1m/s	Velocity 1.5m/s	Velocity 2m/s	Velocity 2.5m/s	Velocity 5m/s
5m Rotor Diameter	40kW	136kW	322kW	6.27kW	5028kW
10m Rotor Diameter	160kW	543kW	1288kW	2514kW	20115kW
20m Rotor Diameter	644kW	2174kW	5154kW	10065kW	80527kW

[1] [1] Calculated over a 1 day period assuming a semi diurnal tide to reflect two tides per day

It can be seen that the output from any Tidal Stream or Tidal Fence turbine will be significantly influenced by the both the stream velocity and rotor size which are both limited by the Strome Narrows topography.

Enhance Flow Rate (Tidal Fence)

The Tidal Fence option see Section 7 requires the partial restriction of the Narrows to increase its velocity. To provide an indication of the suitability of this option URS has undertaken a high level calculation to provide a preliminary indicative flow rate for the Tidal Fence calculations.

From the Admiralty charts a summary profile has been determined. The profile is considered preliminary and ignores local variation across and between the topographies marked on the Admiralty Charts, ground conditions and other natural build up. URS recommends that a detailed survey of the Loch be undertaken before progression of any of the discussed options.

The below graphic represents an estimate of the seabed depth as a cross section of the loch at the proposed crossing point based on the Admiralty Charts to allow the calculation of the flow rates based upon an average channel depth.

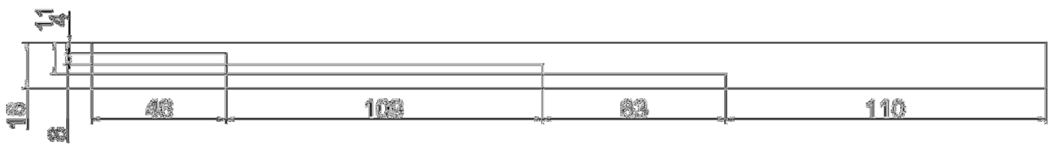

Figure 2 Strome Narrows Subsea Cross-section

From the Admiralty Charts as discussed above the flow rate of the narrows has been considered as 1.5m/s, low for the application of tidal stream devices. Therefore URS proposes reducing the width of the Narrows to achieve a higher flow rate (3m/s).

Fluid dynamics can be applied at a high level. Assuming the volumes and flow are linear across the Narrows and ignoring any losses from turbulence the following equation can be applied.

$\rho A_1 V_1 = \rho A_2 V_2$

ρ= Density of sea water (1025kg/m^3)

A_1= Cross-sectional flow area (based on the width of the Narrows and average depth)

V_1=Velocity of the Narrows natural tidal flow (1.5m/s)

V_1=Velocity through the tidal bridge

For the purposes of the energy calculations and independent of any environmental issues, URS has assumed that the shallow waters can be dammed and the tidal bridges placed within the existing deep water of the narrow. This would reduce the existing width from 220m (summation of the shallow water less than 11m deep) [2] to 110m. Applying the above calculation (see Appendix B) would result in the flow rate of 3m/s. This figure has then been applied to the Tidal Fence option.

[2] The width of the Narrows has been calculated as 328m however the depth is varied. Therefore for URS has simplified the Narrows as a single depth of 16m with a width of 220m

4.2 Costs, Considerations and Limitations

This report includes cost estimates for comparison only. These have been based on idealised scenarios with the information available at the time of writing. Actual generation, construction, operational cost and revenue will be subject to final design and local operation.

4.3 Economics

The development of a tidal generator as part of the roads scheme is expected to require significant capital and operational costs each of which has to be justifiable through the sale of electricity and or benefits during the generator’s lifetime. Within this report URS has investigated the cost of construction of each turbine option, the outlays and potential benefits to enable a feasibility level economic comparison between each of the technologies and their potential to offset the cost of construction of a bridge or tunnel.

4.3.1 *Incentives and Benefits for Tidal Generation*

Tidal generation in Scotland has been identified by the Scottish Government as a significant natural resource which if developed can provide an important contribution to Scotland’s future energy mix and opportunities to export to the rest of the UK and Europe. To progress the development of Wave and Tidal technologies the Scottish Government currently has a number of financial initiatives in place.

URS has reviewed these initiatives and identified three to be included as part of economic evaluation of the technology where applicable. The three initiatives consider in this report are:

Renewable Obligation Certificates (ROC):

ROC are awarded by the Department of Energy and Climate Change (DECC) as credits for the supply of electricity from renewable sources onto the national grid. The number of ROCs awarded is based on the type of generation and its capacity. The development of Tidal and Wave generation is considered important to the Scottish Government and as such its generation has been pushed into an elevated ROCs band. Tidal Stream devices would receive 5 ROCs per MWh up to 30MW, above 30MW the generator will receive 2 ROCs per MWh. While a Tidal Impoundment (tidal Barrage) will receive 2 ROC per MWh for generators under 1GW in capacity.[3]

The ROC price is set by market conditions and as of the 30 September 2013 has an average trade price of £43.29 per unit[4]. The value of ROC may continue to increase due to their limited supply however the current price has been used for the purposes of this report.

It should be noted that the ROC programme will close in 2017 to be replaced by the new Contract for Difference (CfD) programme, for the purposes of this report URS has considered ROCs and CFD as equivalent. It is expected that both programmes will have a limited life span. For the purpose of this report an active period of 50 years has been assumed and thus after 2063 no ROCs or similar rewards will be credited.

[3] Based on 2012- 2013 ROC pricing Scottish Government
[4] ROC price is as per www.e-roc.co.uk/trackrecord.htm

Electricity Price

The electricity price is set by OFGEM based current market demand. Generators bid their expected supply quantities to the system balancer National Grid (NG) whom selects the best priced and most suitability located generation bidder. The Stromeferry tidal generator would participate in this market via the DNO or TSO however unlike other renewable generation the tidal scheme could accurately predict its available supply well into the future. This is advantageous to both NG/OFGEM, as it would allow them to balance the expected loads without the risk of not having the generation available (base load) and to the Stromeferry generation owner, by providing them a more definite income stream.

The price of electricity varies continuously and is again may rise over the life of the generator however for the purpose of this report a value of £51/MWh has been applied to reflect the current mean market electricity value.

Feed in Tariffs (FIT)

Feed in Tariffs are an agreement between the Distribution Network Operator (DNO) and OFGEM to allow the DNO to purchase renewable energy from a local generator at a fixed rate set by OFGEM. They are available to certain types of generation up to 5MW including Hydro/Tidal.

Where the generation is applicable to both ROC and FITs, then the generator can choose to participate in either scheme however they cannot claim both.[5]

The FIT is expected to continue to decrease as more large scale renewables come online therefore in this report it is assumed that these will be discontinued in 2038 after an active period of 20 years.

The current value of FIT for Hydrogenation is:

Table 3 Feed in Tariffs Hydrogenation up to 5MW

	1 April 2013 – 31 March 2014 (£/MWh)
Hydro Generation Station with Capacity Greater than 2MW	33.2

Note that FIT will not be applicable to the Tidal Barrage option as it has a generation capacity greater than the 5MW FIT generation limit.

4.3.2 *Local Loads and Community Gain*

Stromeferry is located in the north west of Scotland approximately 80km from the nearest regional city, Inverness therefore any generation would need to be transmitted through the Scottish Grid adding to the cost of the project. Each of the options has considered possible grid connections requirements; refer to Section 4.4.4 however an alternative may be to supply local residences and industry directly. The area's economy is heavily dependent on tourism and as such there is limited opportunity to develop and distribute the proposed generated power, locally.

Local loads as indicated by SSE network data shows the local demand in the Strome area is approximately 300kVA which includes contributions from:

- South Strome 200kVA
- Strome West 16kVA

[5] www.carbontrust.com

- North Strome 50kVA
- Mid Strome 10kVA
- Cruising Centre Strome 15kVA

These aside there are a limited number of future and other developments which could benefit from a local electricity source these include:

- Kishorn Port: located to the north of Loch Carron, Kishorn Port is a natural harbour pervious used in the construction of offshore oil platforms. Although these activities have now ceased, planning permission has been sought to develop the area as a construction facility for future Offshore Wind and Tidal/Wave generation. If this plan was to be realised there could be potential opportunities to supply the facility directly from the proposed Loch Carron generation.
- Stromeferry Hotel: Stromeferry is home to a small hotel which has recently been granted permission to be redeveloped. This will require a small amount of direct load which again could be supplement from the local generation.
- Fish Farming: the area has a growing aqua culture industry which may require additional supply depending on their farming techniques
- Loch Carron Hotel: has a limited load which could be supplied
- Primary School : has a limited load which could be supplied

These projects have the potential to grow the local population adding further to its electricity demand. The prospect of having local generation to meet this demand could potentially reduce the required network reinforcement in the area and be beneficial to the DNO.

4.3.3 *Operational Costs*

Each of the technologies considered will require on-going maintenance and operational support, the level of which varies from technology to technology and has therefore been evaluated within each of the technologies sections.

4.4 Other Considerations

4.4.1 *Environmental Impact*

Each of the generation options will have the potential to impact on the local environment and will need to be considered as part of the evaluation. Therefore a high level review of these impacts has been included for each of the technologies. It must be noted that in addition to this initial review any option to be progressed will require a detailed EIA to be undertaken, however this is considered outside the scope of this report.

4.4.2 *Risks*

In addition to the above the complexity and scale of any of the options proposed incorporate an inherent level of risk. For each of the options these risks have been evaluated and include:

- Technology risk to reflect the maturity and level of development of the technology. Young technologies are considered to have a higher level of risk due to the limited operational data and their underdeveloped supply chains.
- Construction risk to reflect the complexity and difficulties posed to the options project schedule and ultimate connection time. The construction of any of the options will require working over fast moving water for prolonged periods, further complicated by the northerly location's difficult weather conditions. Any of these factors could slow construction and delay delivery of the project. Furthermore the complexity of construction may render the project financially unsuitable compared to other options under consideration.
- Planning risk to reflect the difficulties in obtaining planning consent and the impact that this will have to the project and its success.
- Economic and political risk; in addition to the capital and maintenance costs of the project, there is further economic risk that market conditions may change or the government may amend current financial benefits. Either of these would reduce the profitability of the project. This is considered common to all of the tidal options and hence has not been evaluated on an individual bases

The above risks can be reduced by further investigation into geotechnical conditions; construction options combined with planning and contract negotiations and technology selection.

4.4.3 *Technology and Site Limitations*

The project has been driven more by the requirement to upgrade the roads network in the area and as such the loch is not considered the most preferential location for tidal generation in the UK this is due to a number of limitations.

Low Tidal Stream Current

Admiralty Charts for the Strome Narrows indicate that the peak flow of the water through the area under consideration (see Appendix A) is estimated at 1.5m/s or 3knots which is considered low for tidal generation and may limit the economics, and in some cases the selection of technologies. In comparison turbine manufactures commonly seek to obtain peak flow rates as high as 5m/s or 10knots for ideal power production, a comparison of output over differing tidal flows can be seen in Section 4.1.2.

Low Water Depth

The Narrows vary in depth from the shallows to a maximum depth of 29m with the maximum depth of each potential crossing option as shown in Appendix D, these being:

- Option A 12 metres,
- Option B 20 metres,
- Option C 16 metres,
- Option D 11 metres.

The water depth limits the technology options and their capacity and thus will be influential in the selection of both. Further the depth of the crossing will also reflect in the complexity and cost of the bridge and therefore the most economical solution will need to be a balance of the requirements of the bridge or tunnel and the potential benefits of the generation.

Shipping and Other Users of Loch Carron

Any solution will need to accommodate the current and future shipping requirement of the loch. Currently the deepest section of the loch is suitable for shipping however if the selected generator was to be placed in these areas of deep water an alternative shipping access would need to be included. The cost of which would need to be justified by the generator output/ sales of electricity. Where the ships are to pass under a bridge a clearance height of 20m is to be considered.

4.4.4 *Grid Connection Options*

Any generation capacity less that exportable directly for local demand as discussed under Section 4.3.2 will need to be exported via the Scottish Grid. The local Distribution Network Operator (DNO) and the Transmission Network Operator (TNO) is Scottish and Southern Electricity (SSE).

At present two existing DNO 33kV lines run along the north and south of the loch and approximately 7.5km further to the south is an existing TSO 132kV transmission line.

The type and size of the required connection will be dictated by the generation capacity. If suitable, URS would recommend that the connection be made to the local 33kV network, subject to the available line capacity of the SSE infrastructure and the future load forecast for the Loch Carron area.

If there was insufficient capacity on the 33kV lines then an alternative connection to the 132kV network would be required. The higher voltage allows a greater level of power to be transmitted with fewer losses however the cost for a connection at this voltage level would be significantly higher due to the increased construction costs and distance to the nearest 132kV substation or line.

To connect from the generator to the local onshore generator substation a subsea cable would be required. The complexity of this arrangement would be dependent on the number of generator units and access to them. As this number varies between the options, the detail for each Option’s connections has been included in Sections 5, 0 and 7. This section will cover the connection from the local substation to the SSE point of connection.

A high level evaluation of each of the options has been carried with the intention of providing an indicative price and to highlight construction issues. The final connection solution will require detailed studies into the impact of the generation connection onto the SSE network.

4.4.5 *Grid Connections Costs*

33kV Connection Option

The areas to the north and south of the Strome Narrows have existing 33kV overhead lines. If sufficient capacity is available on these lines the connection could be made locally. This would provide a cost effective solution, reduce the planning risk and if required, provided local re-inforcement to the 33kV network.

A typical connection at 33kV would be sufficient to export up to approximately 50MVA. The configuration for the connection from the substation to the network may require:

- Teeing into the existing overhead line using a pole top isolator,

- Protection through the addition of a Circuit Breaker on the outgoing line with G59 protection installed,
- A transformer to step up the voltage from the generation voltage to the 33kV SSE network voltage,
- A small building to house the substation, control, protection and communications equipment,
- Inter-tripping which may be required for the protection of the existing network and the generator,
- 1km of underground cable for the connection to the existing 33kV lines,

An approximate cost for the 33kV scheme is estimated at £2M [6]

132kV Connection Option

If there was insufficient capacity on the 33kV lines then an alternative connection to the 132kV network would be required. The higher voltage allows greater power flow with fewer losses however the cost would be significantly greater than the 33kV option. In addition the nearest 132kV circuit is located approximately 7.5km to the south which would require a new 132kV line to be strung through areas of high amenity value possibly complicating the planning process and placing sufficient risk to the project programme.

The requirements for connecting at 132kV are similar to those at 33kV however the higher voltage requires a greater level of containment and insulation, larger conductors adding to the lines weight and tower size, all of which increase the cost.

To allow connection at 132kV the following may be required:

- 132kV, 90MVA transformer to step up the generation voltage to the TSO network voltage of 132kV,
- 132kV line bay including circuit breakers, isolators, earth switch and instrumentation,
- A switching station at the point of connection onto the existing 132kV line,
- 7.5 km of overhead line using steel or concrete structures or alternatively an underground cable,
- A small building to house the substation, control, protection and communications equipment,
- Inter-tripping may be required for the protection of the existing network and the generator,

The estimated cost for connection at 132kV with overhead line is approximately £14.4M. This option poses considerable planning risk therefore an alternative cable option has been costed where the 7.5km route would be underground. This is estimated at £20.4M

Both 132kV options would allow 90MVA of power to be exported. This could be increased by fitting a higher capacity transformer up to the maximum line rating of approximately 200MVA at additional cost.

[6] This price reflects only the connection from the substation transformer to the SSE network. The connection to each of the generator types is discussed below on an individual basis.

5 GENERATION OPTIONS – TIDAL BARRAGE

5.1 Overview

A tidal barrage would require the Narrows to be enclosed by a barrage or dam and the turbines incorporated into its structure. The barrage could then provide a possible foundation for the new roadway.

Tidal barrages have a high generation potential as they can harness the full volume of the loch however they also pose the greatest impact on the environment. The application of a tidal barrage would need careful consideration to ecology and sediment movements before being progressed.

5.1.1 *Description of Technology*

Tidal barrages require the construction of a containment dam which allows the control of the tidal flows to produce a height difference (potential energy calculation see Section 4.1.2). This difference is then used to generate electricity.

Tidal barrages can harness the tidal resource in two ways.

- Ebb Generation works by allowing the tide to flow into the loch until it is filled. Once filled the sluice gates are closed and the tide allowed to recede while the water level in the loch remains level. This would result in a difference of height between the front and back of the barrage. Once this height is sufficient the gates to the turbines would be opened and water allowed to flow over the turbines to generate electricity.
- Two way generation. This allows the tide to travel through turbine gates, as the tide raises and falls. The potential energy builds on the front and back of the barrage to generate electricity in the turbines. As the height is limited to the natural build-up of the water behind the barrage, the potential energy is limited to this height reducing the overall capacity of the generator compared with Ebb Generation. The Two Way Generation may also allow some limited generation from the kinetic energy in the same way as a Tidal Fence see Section 7.

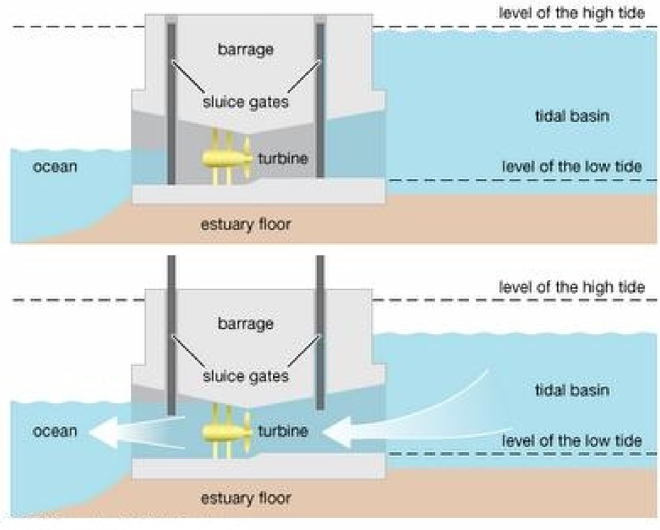

Figure 3 Illustration of Ebb Tidal Barrage

5.2 Implementation and Construction

The proposed option would require caissons to be located across 330m width, of which 110m is greater than 10m in depth to form a barrage. Each caisson would be fastened to the solid sub-structure beneath the loch silt and approximately 8 generators incorporating 8MW bulb turbines[7] would be placed within the barrage where the water depth is sufficient. Sluice gates will be fitted at the entrance to each of the generators to allow the water to be retained once the loch has been filled.

To the side of the barrage a lock channel would be constructed to allow shipping traffic to enter and exit the loch while the loch fills. The cost for the construction of this would require further studies and details surveys and thus considered outside of the scope of this report. For the comparison of options it is assumed to impact similarly on all options and is not a discriminating cost.

A new road can be laid on top of the barrage to allow the completion of crossing road options as shown in appendix A

The above describes a possible solution applying Ebb generation however due to the environmental constraints posed by barrage technology refer Section 5.3.1 URS would recommend that Two Way generation be applied this would allow some current to continue to flow reducing some of the environmental impact. Two Way generation also generates during incoming tides harnessing the tidal flow increasing it availability. This said, Ebb generation has been evaluated within this section and the principle of Two Way generation within Section 7, for comparison purposes.

Barrages are built using caissons which are fixed into the seabed. The area is dredged and slit removed so that the caissons can be fixed firmly to the bedrock or alternative suitable soils.

Bulb Turbines would be located within the barrage to harness the flowing water as shown in Figure 3 Illustration of Ebb Tidal Barrage

[7] Turbine details are based on installed Alstom bulb turbine technology www.alstom.com

5.2.1 *Examples of Technology*[8]

Scheme	Sihwa, South Korea	La Rance, France	Annapolis River, Canada	Jiangxia Tidal Power Station, China	Kislaya Guba, Russia
No. Turbine Units	10	24	1	5	2
Turbine Capacity	26MW / bulb turbine	10MW / bulb turbine	20MW	(1 × 0.5MW) (1 × 0.6MW) (3 × 0.7MW) 3.2MW	(1 × 0.2MW) (1 × 1.5MW) bulb turbines 1.7MW
Annual Energy Production	550GWh	540GWh	50GWh	6.5GWh	N/A
Turbine Diameter	7.8m	5.35m	7.8m	N/A	N/A
Tidal Range	average 5.6m, maximum 7.8m	average 8.2, maximum 13.5m	average 7m	maximum 8.39m	N/A
Energy Production Method	Ebb generation (single direction)	Ebb and flood generation (two way)	Ebb generation (single direction)	Ebb and flood generation (two way)	N/A
Date of Construction	2008 -2011	1961 - 1966	1980 -1984	1980	1968 – 2004
Other		Min head: (ebb generation) 1.2m, increased to +1.75m by pumping Min head: (flood generation) 1.7m			

[8] It must be noted that the examples operate under different tidal conditions to those which occur in Strome Narrows include significantly greater tidal ranges.

5.3 Risks

5.3.1 *Environmental*

The construction of a barrage across the Strome Narrows is anticipated to have significant impact on the loch's ecology and natural sedimentary disbursement.

The loch is home to some of the best examples of Flame Shells beds in the UK. These molluscs are found in shallow fast flowing waters and listed as a significant Natural Habitat as well as being identified in the UK Biodiversity Action Plans Habitat and the Scottish Biodiversity Strategy. The implementation of a barrage would potentially impact on the natural currents, sediment disbursement and habitats of the loch and its inhabitants. Consideration of these and other environmental impacts poses considerable risk to the lochs inhabits, to the projects application for planning and the construction activities. If these issues cannot be address they could potentially render the project un-feasible.

Studies of other barrages implemented around the world have shown that they can impact on the ecology, hydrodynamics of the loch, estuary and water turbidity's and can lead to reduced water quality and/or saltification. Given the nature and scale of the project, these affects can be distributed over a considerable area. Further the barrage construction periods are long, and activities intrusive, adding to the environment risk and their associated impacts.

Therefore detailed studies into the environmental impacts and possible mitigation will be required prior to progressing the Tidal Barrage as an option.

5.3.2 *Construction*

The project will require major civil work under difficult conditions exposing it to substantial risks. The construction of and positioning of caissons in fast moving water poses a number of technical challenges however these possible obstacles are commonly encountered in the marine and hydro construction industries and can be overcome with existing technology.

Working within a sea water environment increases the risk of corrosion, consideration of which will need to be included in the design.

The geographical location of Loch Carron exposures the project to extreme weather which has the potential to disrupt the construction, and as the barrage option requires the longest period of construction, it is the most at risk of delays.

5.3.3 *Planning and Consenting*

The project is expected to face considerable opposition during the planning process by local resident and other users of the loch. This combined with the environmental impact discussed above under Section 5.3.1 and the outstanding natural beauty of the area would make obtaining planning consent a major obstacle.

If this project was to be progressed, URS would recommend a detailed environmental impact (EIA) assessment and planning study is undertaken prior to undertaking any further work.

5.4 Generation Output

The total generated output will be subject to the capacity of the installed generators however for the purpose of this report it is assumed that there would be sufficient room to install the required number of generators to allow conversion of the total available capacity.

The generation will vary throughout the lunar cycles as explained in Section 4.1.2 and be reduce by the turbine inefficiencies and transmission losses. Typical value for hydroelectric generators turbine similar to those used proposed for the barrage[9] is in the range of 80-90%.

In addition to the reduced efficiency caused by the turbines, a height of 1m has been assumed as the minimal head which can effectively drive the turbines thus reducing the total head at which the generation can operate by a further 1m.

The availability of the generators will reflect the change in tides (slack) period and times when the water levels height difference is at less than 1m. Based on load factors of other sites proposed within the UK see Appendix E, a load factor of 0.22 has been applied. This figure reflects an average of these sites load factors.

It is therefore estimated that the total generation for the loch would be 35.47GWh/pa

5.5 Economics

The ultimate cost of a barrage solution will be reduced by utilising the barrage structure in the bridge construction however the civil engineering required for this option is still considered the most significant of all of the options and the most expensive[10].

The majority of the cost will be associated with the civil works to construct the barrage and thus be required from the onset of the project. However to normalise the cost benefits of the generation options, the cost of the barrage or bridge has been considered as a requirement of the selected road option and thus has not been included within this evaluation.

The on-going maintenance is expected to be low due to the nature of the turbines and their housed construction however this will be offset by a number of replacements required throughout the life of the barrage.

The total expected cost for the project is estimated at:

Capital Build Cost = £113.5M.

Substation and Grid connection Cost =£5.75M.

Total capital cost = £119.25M.

Refurbishment and maintenance costs for the life cycle of the Barrage are estimated at £118.4M (120year life) or £987k/pa.

These costs are detailed below

5.5.1 *Capital Expenditure*

The cost to construct the Barrage is difficult to determine at an early stage as the ground conditions and construction methodology has not been determined and there are few operating examples. To provide an understanding of the cost associated with the construction a figure of £65 million reflecting the figures provided within the Mott Macdonald report

[9] Turbine efficiencies are not commonly available due to the commercial sensitivity of the technology thus an estimate has been applied in line with other tidal and hydro plants operating across the globe
[10] Due to the complexity of the project, the cost of the construction would require a detailed design and construction planning exercise to allow refinement. In addition the final solution must consider both the road and generation as a single solution.

(Macdonald, 1994) has been applied. This has been adjusted to inflation and increases in material cost to a prefeasibility cost estimated of £113.5M[11].

Construction of the Generators and Barrage = £113.5M

The cost for the addition of a causeway for the road has not been considered within this evaluation however the barrage structure may offer opportunities for the integration of the road.

5.5.2 *Grid Connection*

The maximum generation level will be during the highest (HAT) and lowest astronomical tide (LAT) cycles. During these periods the output of the generation is estimated at 26.81MW it is recommended that 10% of additional capacity should be provided giving a required grid connection of 29.79MW and hence suitable for connection at 33kV. It is recognised the frequency of HAT and LAT occurring is not defined however it is considered preferential to rate the connection above this level as to not risk limiting the generation.

Table 4 Highest and Lowest Astronomical Tides

Tidal Cycle	High Tide	Low Tide	Difference in Tidal Heights	Maximum Potential Energy	Equivalent daily Power available	Exportable Generation at 0.22 load factor and 10% over rated
Highest/lowest Astronomical Tides	6.4m	0.1m	6.3m	5.14x10^6MJ	59.58MW	29.79MW

As the generation capacity is considerable it is expected that additional re-inforcement to the existing 33kV network would be required including restringing the 33kV line to the nearest substation, Kishorn Hill which is approximately 4.5km from the proposed site. The cost of which is estimated at £750k.

The local substation could be positioned near or within the Barrage with the connections to the generator installed along the Barrage roadway providing ease of maintenance. The local substation would cater for the connection to the generators and transformer and be housed in a small building. The construction of which is estimated at £3M.

The total substation cost is estimated at:

33kV connection = £2M.

Substation = £3M.

33kV line refurbishment work =£0.75M.

Total Grid connection cost = £5.75M.

[11] This figure represents a prefeasibility estimate and is subject to detailed studies, site conditions, construction constraints and number further factors which are still unknown at the time of writing.

5.5.3 *Operating Costs*

The operational and maintenance cost of a Tidal Barrage system will be dependent on the type of equipment supplied and its installation and maintenance cycles. However as the turbine will be housed and protected within the barrage walls the on-going maintenance regime will be reduced. This saving is expected to be offset by the requirement of full refurbishment of the turbines every 20 years (3 time over its life cycle) at an estimated cost of £500k and replacements every 40 years (2 times over its life cycle) at an estimated cost of £2M. A conservative figure of annual 0.5% of the capital cost of the projects[12].

- Annual running Operational and Maintenance cost = £596k/pa

Due to the operational life of the site and equipment, full replacement of the turbines and grid connection equipment will be required. These include

- Replacement of the turbines 40 years (Energy Technology Support Unit, 1994) (2 times over its life cycle) at an estimated cost of £40m based or estimates of (£2.5m per turbine or £20m per replacement)
- Replacement of the substation equipment every 40 years. This considered a complete replacement less the land cost and equivalent to £6m (£3m per substation)
- Full refurbishment of the turbines every 20 years (3 time over its life cycle) at an estimated cost of £900k (£300k per refurbishment)

Total Operational and maintenance cost for the life of the equipment £118.4m (120years) or £987k/pa.

This cost does not include the continued maintenance of the locks and roadway however they will need to be included in the overall road network upgrade evaluation.

5.5.4 *Revenue*

Based on the generation capacities, costs and current benefits a Tidal Barrage would produce the following revenues:

Period (Year Number)	Yearly Generation MWh	Capital Cost (£M)	Operational Cost (£M/pa)	Gross Revenue From Electricity and ROC (£/MWh)	Net Revenue[13] Total Life Cycle (£k)
1 - 51	35,474	119.25[14]	0.987	138	195,421
51 - 120	35,474		0.987	51	57,552
1-120					252,973

Table 5 Estimated Revenue from Tidal Barrage

[12] Report (IEEE, March 1993) identifies an maximum cost of 0.05% of the capital value, to reflect the isolation of the site the full value has been applied

[13] Total Revenue minus Operational and Maintenance costs

[14] To normalise the cost benefits of the generation between the options the cost of the barrage and bridge has been considered as a requirement of the selected road option and thus has not been included within this evaluation.

5.5.5 *Payback Period*

A further exercise has been undertaken to ascertain what revenues may be generated after the payback period and within the design life of the structure which is estimated at 120 years. This work requires more detailed analysis to take account of operating, maintenance, and replacement etc. over the life time of the project.

Payback Period Calculation

((Capital Cost) / ((Yearly Generation x Revenue from Electricity and ROC[15]) – (Annual Operational Cost[16])))= 30 years

From the above it can be seen that a Tidal Barrage option would generate sufficient revenue to cover the costs of the Barrage, the turbines, their housings and the estimated O&M costs. This project would require a high level of capital expenditure, with a long life cycle and expose the owner to considerable risk therefore detailed economic analyses would need to be undertaken to verify the above figures.

5.5.6 *Breakeven*

The following Break Even calculation incorporates the costs noted above and identifies a per unit electricity supply price which would render the option economically viable if applied throughout the option's life cycle. It must be noted that the option maybe subject to significant additional cost which have not been included within this evaluation:

The generation level based on current ROC values and the generation calculated the Tidal Barrage would produce sufficient revenue to breakeven independent of the electricity price therefore an estimate for the total required revenue per MWh only has been calculated.

Break Even Calculation

Breakeven Price = Fixed Cost / Unit Selling Price – Variable Cost[17] (assumes ROC and Electricity prices are variable)

Fixed Costs = Capital Cost +O&M / Life Cycle Period

Unit Selling Price = Revenue per MWh (Number of units sold x Price per MWh)

Breakeven Price = ((119,250,000+118,400,000)/120) / 35474)

Breakeven Price = £56 MWh assuming a unit price per MWh. Note that this is an average price over the 120 years for both ROC and MWh however the ROC will cease during this period.

[15] ROC component of revenue is only applicable until 2063
[16] Calculation includes maintenance cost as an addition to the residual cost of the previous year from the end of year zero
[17] O&M cost are considered fixed costs

6 GENERATION OPTIONS - TIDAL STEAM DEVICES

6.1 Overview

A Tidal Stream Device (TSD) uses the Kinetic Energy of moving water to power turbines, similar to the way wind turbines use the wind. Due to the higher density of sea water in comparison to air (over 800 times) power can be produced at relatively low tidal flow velocities.

TSDs extract energy from the Kinetic Energy/natural velocity of the tidal flow and do not need to impose a water height difference unlike the Tidal Barrage technology.

The solution would require the TSD(s) to be located in the deepest section of the Narrows and thus an alternative shipping route would need to be provided.

6.1.1 *Description of Technology*

A number of TSD technologies are currently in development or at the early stages of commercialisation. The basic principle of TSD, as with wind turbines is to use a collecting surface to transfer the energy in the flow stream onto a generators shaft which can then convert the motion into electricity. As the amount of energy collected is directly proportional to the velocity of the flow and the size of the blades, (see Section 4.1.2) most current technology tend to be large and installed in fast moving water. These can then be separated into two types; horizontal and vertical.

Horizontal Axis

Horizontal Axis machines have the blades positioned around a horizontal turbine shaft similar to conventional wind turbines.

Of the candidate tidal stream technologies horizontal axis units are closest to commercialisation and whilst a number are at TRL 8 [2]18, these units are of such a physical scale that they may be challenging to install in the relatively shallow channel of 10-20 m depth and within a channel width of 60-150 m.

Vertical Axis

Vertical axis machines have the turbine shaft fitted vertically. This technology is less developed however due to the positioning of the blades there is more opportunity to increase the generating capacity of the units in shallow water without increasing overall their height.

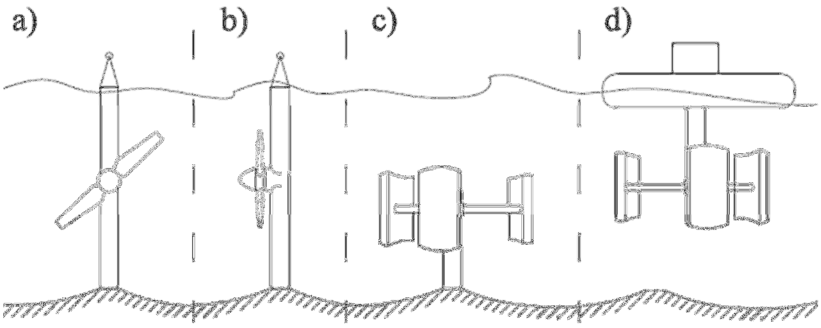

Figure 4 Horizontal (a, b) and Vertical (c, d) Axis Machines

[18] The maturity of devices is commonly represented by the notion of Technology Readiness Level (TRL) [1] where a value of 8 represents an actual system completed and service qualified through testing and demonstration, and a value of 9 represents and actual system proven through successful mission operation.

The current direction of travel in the tidal sector is that a number of manufacturers are moving through prototype testing in open water and are moving to testing of full scale devices prior to commercialisation into arrays. Much focus has been on units at ~ 1 MW size for installation in to areas with a significant tidal resource with a view to driving cost effectiveness by learning and standardisation. This product development is supported by the availability of grants and revenue support from the Renewables Obligation for successful feed into the network.

As an example the Marine Current Turbine SeaGen device requires 25-35 metres water depth to safely accommodate the turbine design and peak spring tidal current velocities of the order 3.0 m/s.

To accommodate shallower water depths the horizontal axis design layout of the Pulse Tidal device can be deployed. The Pulse Stream 100 device was installed in only 9m water depth in the River Humber (refer to Figure 5 Pulse Stream 100 (0.1MW) TSD below).

Figure 5 Pulse Stream 100 (0.1MW) TSD

Pulse Tidal are currently in the advanced stages of designing the next generation of their Pulse Stream unit (refer to artists impression Figure 5). A sizeable device measuring 50m long (i.e. transverse to the flow) by 13m wide. It is reported that the device could generate 1.2MW in 15m of water (if no restriction on overhead clearance is required). In order to be economically viable the device requires a tidal flow rate in the region of 3 - 3.5m/s at peak spring tide.

Figure 6 Pulse Tidal 1.2MW Horizontal Axis TSD

Vertical Axis

Vertical axis machines have the turbine shaft fitted on the vertical and the blades spinning in a horizontal direction. This technology is less developed however due to the positioning of the blades there is more opportunity to increase the generating capacity of the units in shallow water without increasing their height and fit the units directly to a bridge as shown below.

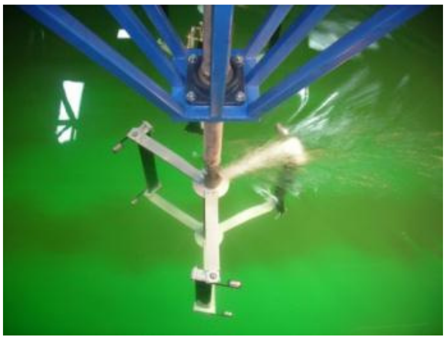

Figure 7 GE Experimental Vertical Axis Machine Supported Above

6.2 Implementation and Construction

In terms of resource and technology, the Loch Carron tidal velocities are low compared to current state of art devices which are not optimised for this level of flow; furthermore the devices of the appropriate physical scale are below the target economic size and should be considered as prototypes.

At present the most suitably advanced technologies are the Horizontal Axis devices. A number of these devices would be located in the deepest section of the loch in a suitable shaped array configuration. The final design of this array would be subject to future surveys and evaluation of tidal flow.

It is expected that the array would restrict the type of craft that could use the loch so as with the Barrage Option above a shipping canal would need to be constructed so that ship access could be maintained. The cost for the construction of this would require further studies and details surveys and thus considered outside of the scope of this report. For the comparison of options it is assumed to impact similarly on all options and is not a discriminating cost.

Conventionally each of the turbines would be located on foundations which would be secured to the bedrock. These foundations would only need to be of sufficient size to attach the turbine bases limiting the impact to the seabed. Alternative schemes could be considered to attach the turbines to the bridge structure.

An onshore substation will need to be constructed at a convenient location to allow connection to the SSE network. Each of the turbines would in turn feed the substation through a network on subsea cables.

6.2.1 *Examples of Technology*

There are currently a number of different types of TSDs being field tested (vertical, horizontal and shroud or open centre) and connected to the grid.

To develop marine energy at a commercial scale wave and tidal, marine energy parks have been established in Scotland at Pentland Firth and Orkney Waters and in south west England stretching from Bristol to Cornwall, several devices have been tested and trialled.

Several full scale trial TSD sites have been in operation around the UK;

- Marine Current Turbines: Seagen - Strangford Lough, Northern Island

    Type: seabed mounted tidal stream generator using axial flow rotors

    Commissioned: April 2008, connected to grid July 2008

    50% funded by DTI

- Open Hydro Group: Open-centre turbine – Orkney

  Type: sea bed mounted open centre tidal stream generator

  Commissioned: 2006, connected to grid May 2008

- Pulse Tidal: Pulse Stream 100 – River Humber, Hull

  Type: seabed mounted tidal stream generator using oscillating hydrofoils

  Commissioned: 2009, exporting the power to Millennium Chemicals (plant on the South bank of the estuary)

Tidal stream technology has not yet been constructed on a commercial scale. However, there are currently plans to construct tidal arrays at the following sites;

- Scottish Power Renewables plan to install 10no. 1MW Andritz Hydron Hammerfest HS1000 Tidal Turbines which will be fully submerged on the seabed just south of Port Askaig, Islay (Sound of Jura).
- Kylerhea, Skye: Pulse Tidal plan to install 8 no. turbines and Marine Current Turbines intend to install 4no. SeaGen turbines.

6.3 Risks

6.3.1 *Environmental*

As TSD technologies do not require the construction of a barrage their associated environmental impact is significantly reduced in comparison to Barrage Options. Further TSD only take a proportion of the tidal stream which, if confirmed was sufficient could allow fauna to continue to exist with minimal impact.

The positioning of the TSD foundation would require small areas of seabed to be excavated, these areas would typical be less than 10m2 and again could be selected to minimise their impact.

The rotating blade of the TSD pose some risk to the marine and bird life in the area, the impact of which would need further study during the early stages of the project. Studies on other TSDs have not been conclusive.

6.3.2 *Construction*

The construction risk of a TSD is considerably less than those associated with the Barrage Option. The units only require small foundation to be positioned on the sea floor and can use a barge during installation.

The simpler installation method limits the time required on the water during the installation to the time it takes to position and fit the turbines. This reduces the construction complexities and any associated weather delays.

The TSD height will be limited by the water depth of the channel and as such may limit the position and configuration of the array. This may further restrict construction options.

A TSD Option will require a more complex subsea cable configuration as all connections will run along the seabed however this is considered minor in comparison to the civil construction challenges of the Barrage.

Existing tidal stream concepts have focussed on open water solutions where the integration with the structure is a key part of the overall concept. Alternative schemes could be considered where turbine attachment and grid connection is made via a bridge structure. In the event of wishing to use the bridge structure as part of the turbine support, the impact of the additional loads will need to be taken into account.

6.3.3 *Planning and Consenting*

It is expected that the development of a TSD solution will meet considerable resistance from local residents and other users of the loch. The implementation of the turbines will limit access to some areas and local user could potentially not identify with the benefits of the proposal.

However in comparison to the tidal Barrage Option, the reduced environmental impact specifically to the sea bed offers greater opportunities to progress a TSD solution through planning.

6.4 Generation Output

Due to the lack of tidal data available within the constraints of this scoping study it is difficult to assess the power generation capacity of a TSD. Any increase or decrease in current speed will have a dramatic effect on power generation as power output is proportional to the cube of the tidal velocity.

In the absence of detailed tidal flow data URS has undertaken an estimation exercises to rationalise the variations of tide across through the Narrows. This has been based on the rule of 12 and rule of 3rds for tidal velocity variation during a given tide.

These indicative pre-feasibility calculations considerers the following parameters:

- Tidal flows will vary from the spring tide to the neap tide across the 14 day cycle. The variation of the flow rate over these 14 days is linear.
- A generic tidal unit with a blade diameter of 10m has been used. It is expected that multiple units will be able to be installed however these will be limited by the size of the narrow.
- A capacity factor which incorporates the losses associated with the generation of 0.4 has been applied.
- That the generator will only generate at flows greater than 1m/s.
- Applying a turbine with approximately rating of 50kW.
- The resulting output of a single turbine is 50kW and has a yearly estimated generation capacity of 61MW/h pa.

Based on a width of 110m reflecting the deepest part of the Narrows an estimated 4 turbines could be located. This would provide a 5 meter buffer (or 10m between blades) for each of the turbines and leave sufficient clearance to the sloping topography. Not considering the interposing turbulence of the generators, the output generated is estimated at 200kW or 0.245GWh per year. Additional turbines could be placed in an array to increase this figure however this would require detailed modelling and is considered outside the scope of this report.

6.5 Economics

Capital Build Cost = £10 M.

Substation and Grid connection Cost =£1.0M.

Total capital cost = £11M.

Refurbishment and maintenance costs for the life cycle of the TSD are estimated at £1.2M or £30k per year.

6.5.1 *Capital Expenditure*

The cost of installation of a tidal generation system can vary considerably between technologies and installations. Therefore URS has sort to review current technologies based on information provided from the manufactures. Pulse Tidal has estimated a pre-feasibility price at £5M per 1.2MW unit. URS considered the size of this unit potentially too large for operation in the Strome Narrows however due to economies of scales URS considered its cost will be comparable to half that of the 1.2MW unit and therefore have assumed an installed unit value for a small scale prototype generator at £2.5M.

This gives a pre-feasibility cost to install the 4 generators at £10M this figure includes limited civil and construction works required to install the units.

The cost for the addition of a causeway for the road has not been considered within this evaluation. A TSD option could be either freestanding or be incorporated into the construction of a bridge.

6.5.2 *Grid Connection*

Due to the relatively lower generation capacity it is expected that the TSD will be able to connect the 33kV or 11kV networks and have a reduce substation size and associate cost.

The interconnection between the generator units will require subsea cable however the level of power for these connection will reduce their cost considerable, further if a bridge or tunnel option was progress then these structures could potentially be used to support the turbines and cables

33kV connection and subsea cables = £0.5M

Substation = £0.5M

Total Grid connection cost = £1M

6.5.3 *Operating Costs*

The expected operating and maintenance cost of the TSD will be considerably higher than those of the other technologies as the generators will be located in the central stream with no protection. Further as they are located in isolation, access will be more difficult than the Barrage. Pulse Tidal have provided estimates for maintenance at approximately £150K per unit. URS believes that the smaller units will be approximately 5% of the cost of the larger units due to them being considerably easier to remove and repair.

URS therefore considered an estimated prefeasibility full life cycle cost of the option at £0.6M or a cost per unit at £7.5k/pa (£30k/pa for the 4 units).

6.5.4 *Revenue*

The TSD will be entitled to all of the financial initiatives identified within section 4.3.1 however due to the low flow rates of the Narrows and associated poor generation output, the financial benefits of this scheme are limited.

The following summarises the expected revenue from the TSD option:

Note that this is dominated by the O&M costs. Based upon the statement that economic tidal flows are 2 x that available, the available energy is ~ 1/8 that would be available from the machine under optimum conditions.

Table 6 Expected Revenue of TSD

Yearly Generation (MWh)	Capital Cost (£M)	Operational Cost (£M/pa)	Gross Revenue From Electricity and ROC (£/MWh)	Gross Revenue Pa (£k)	Revenue Net Total Life Cycle (£k) over 20 yrs
245	11	0.03	267[19]	35.4	711

6.5.5 *Payback Period*

The estimated life of these units is considered to be 20[20] years based on the average life of a wind turbine. The assumption is based on the similar operation of wind turbines and TSD technologies. It can be seen that the estimated revenue in insufficient to achieve a payback within the life time of the equipment and thus the TSD option is considered to be a non-feasible solution.

Payback calculation

(((Capital Cost)/ ((Yearly Generation x Revenue from Electricity and ROC[21]) - (Annual Operational Cost[22]))) = >20 years

For this Option to progress, either the price of electricity or the produced generation output would need to increase.

[19] Price assumes application for ROC not FIT
[20] Turbine life taken from www.vestas.com/en/about-vestas
[21] ROC component of revenue is only applicable until 2063
[22] Calculation includes maintenance cost as an addition to the residual cost of the previous year from the end of year zero

6.5.6 *Breakeven*

The following break even calculation incorporates the costs noted above and identifies a per unit electricity supply price which would render the option economically viable if applied through the options life cycle. It must be noted that the option maybe subject to significant additional cost which have not been included within this evaluation:

Break even calculation

Breakeven Price = Fixed Cost / Unit Selling Price

Fixed Costs = Capital Cost + Variable Cost/ Life Cycle Period

Unit Selling Price = Revenue per MWh (Number of units sold x Price per MWh)

Variable Cost = Maintenance Cost

Breakeven Price = (11,000,000+1,200,000 / 20) / ((245 x £/MWh)))

Breakeven Price = £ 2,490/MWh

Fixed Costs = Capital Cost – ROC Contribution + Variable Cost/ Life Cycle Period

Unit Selling Price = Electrical Generation Revenue (Number of units sold x Price per MWh)

Breakeven Price = (11,000,000-1,060,605+1,200,000 / 20) / ((245 x £/MWh)))

Breakeven Price = £ 2,273/MWh where ROC are set at current value

7 GENERATION OPTIONS – TIDAL FENCE OR BRIDGE

7.1 Overview

A tidal fence or bridge comprises of a line of underwater tidal current turbines. The tidal flow is normally constricted (by means such as a causeway) to a reduced cross-sectional (width) to induce higher flow velocities which then drive turbines. Some devices can be built into the structures of bridges which would further support their application at Stromeferry

"Tidal fencing" is a relatively new technology and is still under development and it is understood that no schemes are currently in operation. A tidal fence/bridge would have significantly less impact on wildlife and the environment than a tidal barrage.

The solution would require restricting the loch to a small channel thus an alternative shipping route would need to be provided.

7.1.1 *Description of Technology*

Two companies have assisted in the assessment undertaken by URS to date and their inputs will be used for this assessment. It must be noted that neither of these units have been installed at commercial scale and thus the outcome of the evaluation can only be considered at a pre-feasibility level.

Pulse Tidal

Due to the shallow water design Pulse Tidal devices could be incorporated into a bridge structure across the Strome Narrows. The Pulse Stream 100 (PS-100) device is currently in operation and available at a cost of £1 million per unit and is rated at 0.1MW output. The advantage of this unit is that it can be deployed in 5m of water and is rated for 2m/s current speed. Even considering the shallow depths at Strome Narrows it may still be possible to deploy multiple PS-100 devices. If a higher current velocity was achieved then this would greatly increase the power output (power output is proportional to the cube of the velocity).

The Pulse Tidal next generation device is in the advanced stages of design but is approximately 3-4 years from going to market. Each device will cost in the region of £5 million or £4.5 million if it was mounted in a bridge or similar structure and is rated at 1.2MW at 3 to 3.5 m/s peak spring tide current velocity.

Note both of these devices would require the tidal stream of the Narrows to be increased with a tidal fence to achieve the above generation.

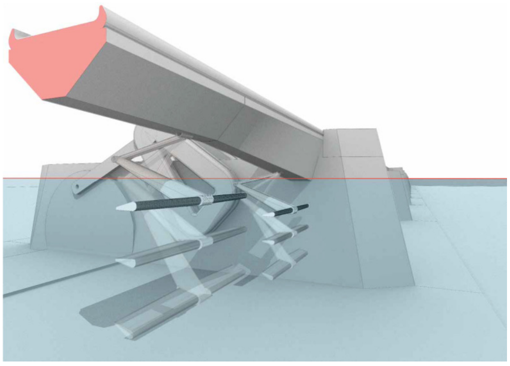

Figure 8 Artists Impression Pulse Tidal Bridge Thames Estuary

Blue Energy

Blue Energy Inc. is currently developing a tidal bridge using vertical-axis turbines with four fixed hydrofoil blades and an integrated gearbox and electrical generator assembly. The rotation of the turbine is unidirectional on both the ebb and the flow of the tide.

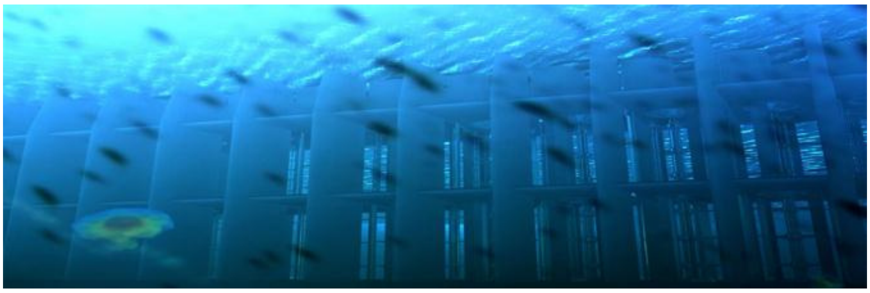

Figure 9 Artists Impression Blue Energy Inc. Tidal Fence (Bridge)

7.1.2 *Examples of Technology*

There are currently no commercial scale technologies installed as a tidal fence. Tidal Pulse and Blue Energy gives a good representation of the current technology as it stands however to scale these up while increasing the flow rate poses a number of technical challenges.

As these and other prototype develop their suitably will need to be assess against their own merits.

7.2 Implementation and Construction

The implementation of the tidal fence project would require a structure to be built to restrict the flow. It would require considerable civil works. This structure would not act as a barrage and thus the complication of construction would be considerably less however it would need to be able to direct a proportion of the flow so that its velocity can be increased

The bridge structure would require piles foundation to be located within the seabed on top of which will be constructed piers which the bridge pillars can be placed upon.

A structure would be built between the bridge piers. This would be used to position the generation units as shown in Figure 8 and Figure 9. Alternatively the tidal fence could be hung from the bridge structure to reduce the impact on the seabed and provide better access.

An onshore substation needs to be constructed to allow connection to the SSE network. This would be connected via subsea cables to the generators with the bridge structure providing support.

As with the other options a new shipping channel or lock would need to be constructed to allow existing water traffic to navigate into and out of the loch. The cost for the construction of this would require further studies and details surveys and thus considered outside of the scope of this report. For the comparison of options it is assumed to impact similarly on all options and is not a discriminating cost.

7.3 Risks

7.3.1 *Environmental*

The implementation of a tidal fence device presents a number of potential impacts to the environment of Loch Carron. The construction will require restricting a large area of the Loch's Narrow. This will have an effect on the natural tidal steam and conversely the Loch's inhabitants including the Flame Shells. However as the flow will be continuous and proportional to the number of turbines, careful planning and design to maintain a sufficient flow within the natural limitations suitable for the loch ecology could allow this impact to be mitigated.

The foundations will be plied into the bedrock and sized to support the bridge. Although these will be of considerable size they will be limited in number thus have a much reduce impact compared with the Barrage. The alternative option would be to fix the generation structures to the bridge which could further reduce the tidal fences impacts.

The rotating blades of the tidal fence pose some risk to the marine and bird life in the area, the impact of which would need further studying during the early stages of the project however due to the relatively slow speed of the turbines it is expected that that the overall impact will not be severe.

7.3.2 *Construction*

The construction risk of a Tidal Fence is considerably less than those associated with the Barrage option although greater than those of a TSD as both the foundations and the generator support structure will need to be constructed. However there is no major experience base for mounting devices of this technology.

Existing horizontal axis concepts allow for the device to align with the flow direction either by yawing the device into the direction of flow or by allowing for reverse pitch of the blading so that the device can accept flow in either tidal direction. Within the context of a tidal bridge, the device will need to cater for a reverse pitch operation.

Vertical axis devices are able to cater for flow from any direction, however efficiency tend to be lower because of the degraded flow conditions on to the 'downstream' blading.

Clever design and construction of the generator support structures may reduce the time required on the water during the installation and the associated complexities caused by weather delays.

As the structure is built and the tidal stream increases, work will become more difficult and technically challenging.

The connection to the substation will be made via network of subsea cables; these can be contained within the generator support structure and/or the bridge structure.

7.3.3 *Planning and Consenting*

It is expected that the development of a Tidal Fence solution will meet with considerable resistance from local residence and other users of the loch. The implementation of the turbines will limit access to some areas of the loch and local user could potentially not identify with the benefits of the proposal.

The size and construction methods applied will determine the impact to the ecology and will be subject to the limitations of the planning application however in comparison to the Tidal

Barrage option the reduce environmental impact offers greater opportunities to progress a Tidal Fence solution

7.4 Generation Output

The generator output will be proportional to the ability of restrict the tidal flow of the Narrows and thus increasing the flow velocity. If the existing flow rate can be increased significantly the possible generation output can be increase by a cubic function. The below table show estimated generation capacity at varying flow rates:

Table 7 - Estimated Power Output Tidal Fence[23]

Flow Velocity (m/s)	Power Output (MW)
1.5	0.4
2.5	2.0
3.0	3.48
3.5	5.53
4.0	8.24
5.0	16.12

The installed generation and flow rates will need to consider the impact on the environmental as described in Section 6.3.1.

Based on the hypothetical flow rate of 3m/s and 8 generators units the estimated generation capacity is 3.48MW with a yearly generation of 6.1GW/h

7.5 Economics

On the basis that a flow velocity of 3m/s can be achieved by restricting flow through Strome Narrows, assuming a 30% efficiency factor and an annual power production of 6.1GWh the cost estimate for a Blue Energy vertical turbine tidal bridge is as follows:

Capital Build Cost = £26.9M.

Substation and Grid connection Cost =£3M.

Total capital cost = £29.9M.

Refurbishment and maintenance costs for the life cycle of the barrage are estimated at £314k or £15.7k/pa.

7.5.1 *Capital Expenditure*

Blue Energy Inc has provided an estimated cost of £35million for 12no. Horizontal turbines however after review URS believes that there is insufficient room for this number of turbines and has considered 8 as being more practical thus reducing the capital cost to £23.3M.

The cost of the structure to house the turbines and its installation is estimated at £200k per turbine = £1.6M.

To restrict the flow to the area of the narrows were the turbines will be located will require an additional structure to be constructed. This structure could form part of the bridge however there would be an additional cost associated with the construction. This has been assumed at a prefeasibility estimate of £2M.

The total estimated capital outlay for the turbine construction is = £26.9M.

[23] These are feasibility level estimates based on URS assumptions that there is sufficient room for 8 generators and the rule of 3rds

The cost for the addition of a cause way for the road has not been considered within this evaluation. The Tidal Fence Option will require supports to span the width of the Narrows which may be able to be used within the construction of the bridge and offer possible avenues to a reduction in its cost. .

7.5.2 *Grid Connection*

The maximum generation level will be during the highest and lowest astronomical tide cycles. During these periods the output of the generation is estimated at 3.48MW it is recommended that 10% of additional capacity should be provided requiring a grid connection of 3.8MW suitable for connection at 33kV see Section 4.4.4.

Local substation can be positioned near or within the bridge with the connections to the generator installed along the bridge structure. The local substation would cater for the connection to the generators and be housed in a small building. The construction of which is estimated at £1M.

The total substation cost is estimated at:

33kV connection = £2M.

Substation and cable connections= £1M.

Total Grid connection cost = £3M.

7.5.3 *Operating Costs*

Estimated operating cost of Tidal Bridge(Fence) turbines has been provided considering a 20 year life cycle. The figures below have been provided by the manufacture as a prefeasibility estimate, note that as these turbines will be contained within a fixed structure their O&M cost are less than that the TSD included above:

Operation and maintenance of turbines = 3% annual revenue = £4.8kpa

Maintenance variable = £1.8/MWh. = £10.9kpa

Total estimated annual operating cost = £15.7kpa.

7.5.4 *Revenue*

The Tidal Fence Option will be entitled to all of the financial initiatives identified within section 4.3.1.

The following summarises the expected revenue from the Tidal Fence Option

Table 8 Tidal Fence Estimate

Yearly Generation (MWh)	Capital Cost (£M)	Operational Cost (£M/pa)	Revenue From Electricity and ROC (£/MWh)	Gross Revenue From Electricity (£k) pa	Revenue Net Total Life Cycle (£k) over 20 years
6,100	29.9	0.0157	267[24]	1629	32,006

[24] Price assumes application for ROC not FIT

7.5.1 *Payback Period*

The estimated life of these units is considered to be 20 years based on the information provided by manufacturers. After review of the technology the estimated revenues are considered to cover the capital cost of the project by the end of the 18th year.

Payback calculation

(((Capital Cost) / ((Yearly Generation x Revenue from Electricity and ROC[25]) - (Annual Operational Cost[26])))= 19 years

From the above it can be seen that a Tidal Fence option would generate sufficient revenue to cover the costs of the turbines, their housings and the estimated O&M costs however it would provide limited additional revenue to supplement the road project.

7.5.2 *Breakeven*

The following break even calculation incorporates the costs noted above and identifies a per unit electricity supply price which would render the option economically viable if applied through the options life cycle. It must be noted that the option maybe subject to significant additional costs which have not been included within this evaluation:

Break even calculation

Breakeven Price = Fixed Cost / Unit Selling Price

Fixed Costs = Capital Cost + Variable Cost / Life Cycle Period

Unit Selling Price = Revenue per MWh (Number of units sold x Price per MWh)

Variable Cost = Maintenance Cost

Breakeven Price = (29,900,000+314,000/ 20) / (6,100 x £MWh)

Breakeven Price = 247£/MWh

Breakeven Price = Fixed Cost / Unit Selling Price

Fixed Costs = Capital Cost – ROC Contribution + Variable Cost / Life Cycle Period

Unit Selling Price = Electrical Generation Revenue (Number of units sold x Price per MWh)

Variable Cost = Maintenance Cost

Breakeven Price = (29,900,000-26,406,900+314,000/ 20) / (6,100 x £MWh)

Breakeven Price = 31£/MWh with current price of ROC applied

With the application of the tidal fence as described above and current market conditions this option could operate with a reduction in the strike price of electricity to £31/MWh.

[25] ROC component of revenue is only applicable until 2063
[26] Calculation includes maintenance cost as an addition to the residual cost of the previous year from the end of year zero

8 EVALUATION OF TECHNOLOGIES

Table 9 Summary Matrix of Options

	Environmental Risk	Construction Risk	Technology Maturity Risk	Planning Risk	Generation Output	Cost
Tidal Barrage						
TSD						
Tidal Fence						

Considered feasible	
Considered a non-feasible	

8.1 Tidal Barrage Option

The tidal barrage would have the highest level of capital expenditure and greatest level of construction activities as it would require damming the full width of the narrows. The construction activities will have considerable risk of construction delay and cost escalation due to the size and nature of the project.

The generating capacity of the Tidal Barrage solution indicates that is has the greatest of all the options. It is also considered to require the largest capital expenditure. Based on the current estimates proposed that the generation revenues would be sufficient to cover these cost over its life cycle with a payback period estimated at 30 years under the scenario proposed. However this option is considered to hold the greatest inherent risk due of the options due to its 120 year life, the large initial capital costs and the longevity of its proposed operations.

The project is expected to have a serve impact on the environment and considering the local ecology and fauna in particular the Flame Shells, and the consenting difficulties associated with a build of this scale in the sensitive environment of the Loch, URS would not recommend this option on environmental grounds unless suitable mitigation can be determined.

A Tidal Barrage may allow the incorporation of a causeway into its design without the requirement for an additional bridge or structure, this would be subject to further studies

8.2 Tidal Stream Devices Option

The TSD option offers a solution which could be environmentally feasible and due to the reduce scale of the project provide a much reduced risk profile and a more simple construction.

However due to the limited generation capacity produced by the low flow rates of the narrows, the economics of this option are not considered feasible under the current market conditions. It is recognised that energy prices could increase considerably over the life cycle of the generator to a point where they become feasible. URS has not considered these increases in its evaluation as they believe these will be driven by market forces and cannot be applied without basis. However URS would recommend that a TSD solution be reconsidered in the future as the market conditions evolve.

The application of a TSD option would require a bridge to be built to allow completion of the crossing, the cost of which would need to be considered in a joint evaluation as part of the road options. Whilst novel options could be considered for integrating the turbines into the bridge structure, there are no current examples of such integrated solutions in operation.

8.3 Tidal Fence Options

The tidal fence option presents the most feasible options of the three considered within this report, under current market conditions the option will payback its associated costs within the life of the option however this would be during the 18th year and thus the potential revenue to cover the road construction cost would be marginal.

The Tidal Fence solution would need to provide sufficient mitigation against damage to the ecology and other environmental consideration. Detailed studies must be undertaken to insure any impact will be of an acceptable level.

The tidal fence technologies are still being developed and as such URS would highlight that their infancy poses a number of inherent risks if they were to be applied. Currently they cannot be considered as off the shelf technologies and hence there is a significant risk that any performance assumptions cannot be substantiated. As such URS would recommend that a review of the tidal fence option be undertaken at the onset of the project considering any relevant current and future projects.

The application of a tidal fence could be designed to provide structural support across the narrow suitable for the bridge crossing, benefiting the economics of the option.

8.4 Options Summary

The following Table 10 Summary of Generation Options**Error! Reference source not found.** provides a summary of the options for comparison. It highlights the scale of the different technologies and the differences in capital cost, generation and possible revenues.

	Tidal Barrage	Tidal Stream	Tidal Fence
Capital Cost (£m)	119.25	11	29.9
Yearly Generation (MWh)	35,474	245	6,100
Net Annual Revenue (£k)	3,908 Year1 -50 822 Year 50 - 120	65	1,628
Gross Annual Revenue (£k)	4,895 Year1 -50 1,809 Year 50 - 120	35	1,613
O & M Cost (£k/pa)	987	30	15
Estimated Electricity Buy Price £MWh	51	51	51
Payback Period (Years)	30	N/A (See Note 1)	19
Operating Life (Years)	120	20	20
Breakeven Price (£MWh)	56	2,490	247
Breakeven Price (£MWh) at current ROC price	N/A (See Note 2)	2,273	31

Table 10 Summary of Generation Options

Note 1 The Tidal Stream Option will not produce sufficient generation to payback the capital and annual O&M within the life time of the equipment

Note 2 The Tidal Barrage Option will produce sufficient generation to breakeven independent of the price of ROCs

9 CONCLUSION

The report has identified that there is a number of potential tidal options available in the market at a commercial or pre-commercial level of development which could be applied to the Stromeferry road network upgrade scheme.

The location has been determined by the need to develop the road network in the area and not the optimum site for tidal energy development. Whilst the tidal ranges are significant the tidal resource is not the most advantageous when compared to other sites in the UK. The result is a lower than optimal tidal velocity and a number of ecological constraints.

Of the three options which applied different technologies the Tidal Barrage, TSD and Tidal Fence, the Tidal Fence appears the most feasible however the technology is the most immature and the least demonstrated.

The Tidal Barrage is historically the most widely applied technology and offers the greatest generation capacity however due to its environmental impact and high capital cost its application in the Stromeferry Narrows is considered to pose considerable risk, the greatest of all the options. For this option to be considered further, detailed economic and environmental studies will be required including possible mitigation or avenues to obtain consenting. This option is not considered feasible unless the environmental constraints can be addressed.

TSDs are considered to be feasible as a technology to be applied however due to the relativity low flow rates of the Narrows the generated capacity under current market condition is of a level that would not justify this option. Hence URS would not recommend a TSD option under these conditions. If market conditions were to improve then this Option may become feasible.

The Tidal Fence Option presents a possible more economic option by using TSD technology rather than vertical axis technology. The option proposes to funnel the tidal flow increasing its flow rate. This report has considered a rate of 3m/s based on the topography of the Loch. At this rate the generated output would be sufficient to payback the capital and operational cost of the devices however this would take approximately 18 years of the 20 year operating life of the equipment and thus provide minimal additional revenue to supplement the roads project.

In addition the Tidal Fence would require significant alteration to the Narrows which presents a number of impacts to the environment. Further the options will require a prolonged construction period and the limited data available due to the technology's infancy increase the risks to the project and the assumptions made within this report.

All of the options would need to consider further the requirements of the current Loch users and planning constraints. In regard to ship movements this may require significant additional costs to construct shipping access ways. These costs would be above those specified within the report. Estimate for which would require further investigation, if an option was to proceed.

Out of the three options presented within this report, the Tidal Fence is considered the most promising and should be considered further as the technology develops and the project approaches the construction phase.

URS considered under the current market conditions that only the Tidal Fence and Tidal Barrage Options subject to consenting and environmental consideration would provide a financial benefit to the road scheme. With favourable changes in market conditions additional opportunities to progress tidal generation within the Stromeferry Narrows may arise.

Further work could concentrate on developing a scheme mitigating the risks by combining the desirable elements of each option, reviewing methods to locally increase the flow velocity on to a proven device design, with minimum impact to environmentally sensitive areas and with an optimised structure, however this would result in a lower level of energy generation offering less opportunity to offset the fixed costs of the infrastructure and potentially high costs of low volume, small scale devices.

10 REFERENCES

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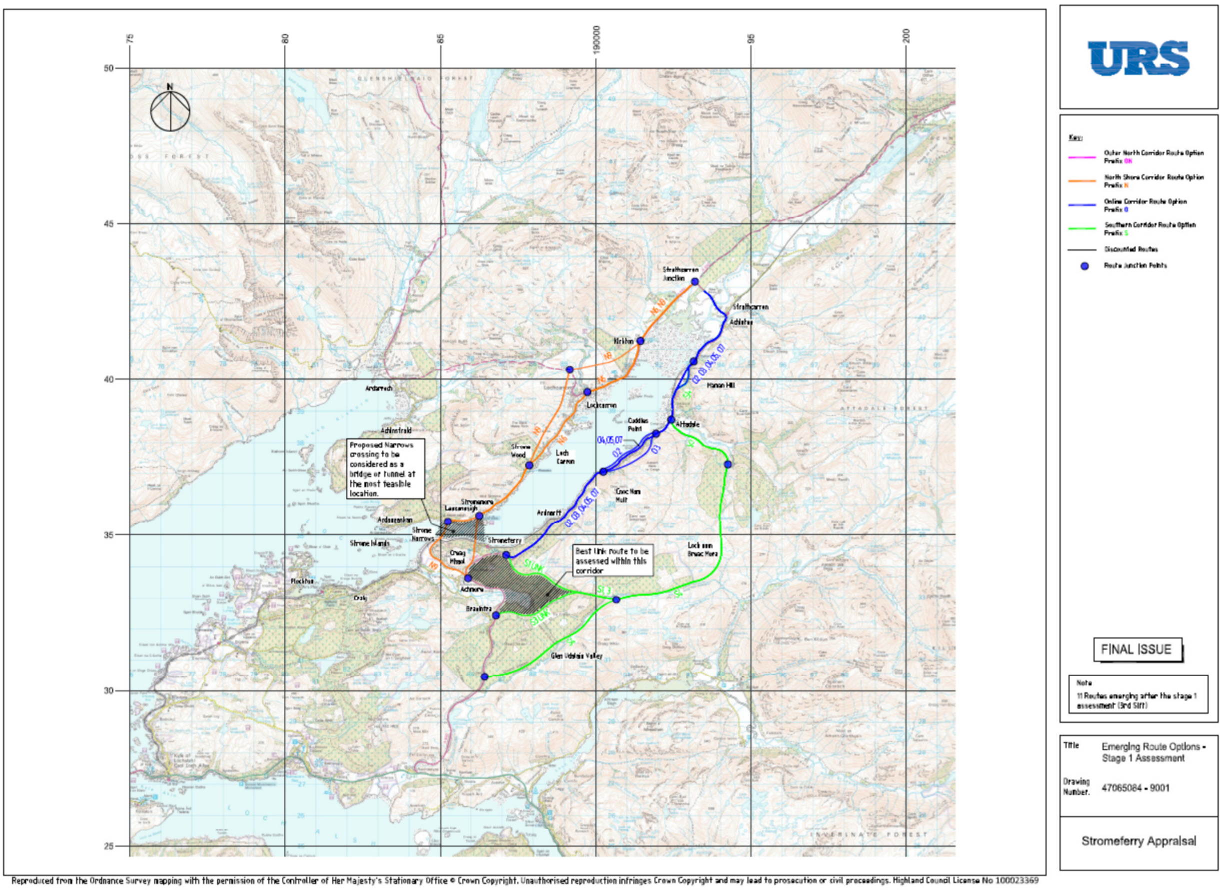
APPENDIX A STUDY AREA UNDER CONSIDERATION AND ROAD OPTIONS



APPENDIX B ENERGY CALCULATION

Potential Energy Calculation

The following calculation gives the total potential tidal energy for Loch Carron. This has been based on the spring tidal range however this will reduce throughout the lunar cycle.

$E_p \quad = 0.5 \rho g A_b \triangle h_b^2$

$= 0.5 \times 1025 \times 9.807 \times 12.90 \times 4.8\text{^}2$

$E_{p=}$ Potential Energy

ρ= Density of sea water (1025kg/m^3)

g= acceleration due to gravity (9.807m/s^2)

A_b= Horizontal area of the enclosed basin (12.90km^2)

$\triangle h_b$= mean tidal range in the basin (4.8 m for spring tide, 1.8 m for neap tide)

The factor 0.5 accounts for the reduction in hydraulic head across the barrage as the impounded water empties

E_p =1493GJ per tidal delta

Based on the two tides per day and averaged over a day is equivalent 34.58MW

Kinetic Energy Calculation

$P_k = ½ \rho AV^3$

ρ= Density of sea water (1025kg/m^3)

A = The swept area of the turbine rotor. As no turbine has been identified at this stage an assumed area of 78.5m^2 based on a maximum rotor diameter of 10m placed in 20m of water with 5m clearance to the seabed and surface has been applied.

V= The undisturbed stream velocity. This has been assumed at 1.5m/s based on stream velocities identified within Admiralty charts and does not consider the variations of velocities across tidal ranges.

$P_k = ½ \rho AV^3$

P_k =0.5 x 1025 x 79 x 1.5^3

P_k = 136kW

Tidal Flow Rate through a Restriction (Tidal Fence)

$\rho A_1 V_1 = \rho A_2 V_2$

ρ= Density of sea water (1025kg/m^3)

A_1= Cross-sectional flow area (based on the width of the Narrows and average depth)

V_1=Velocity of the Narrows natural tidal flow (1.5m/s)

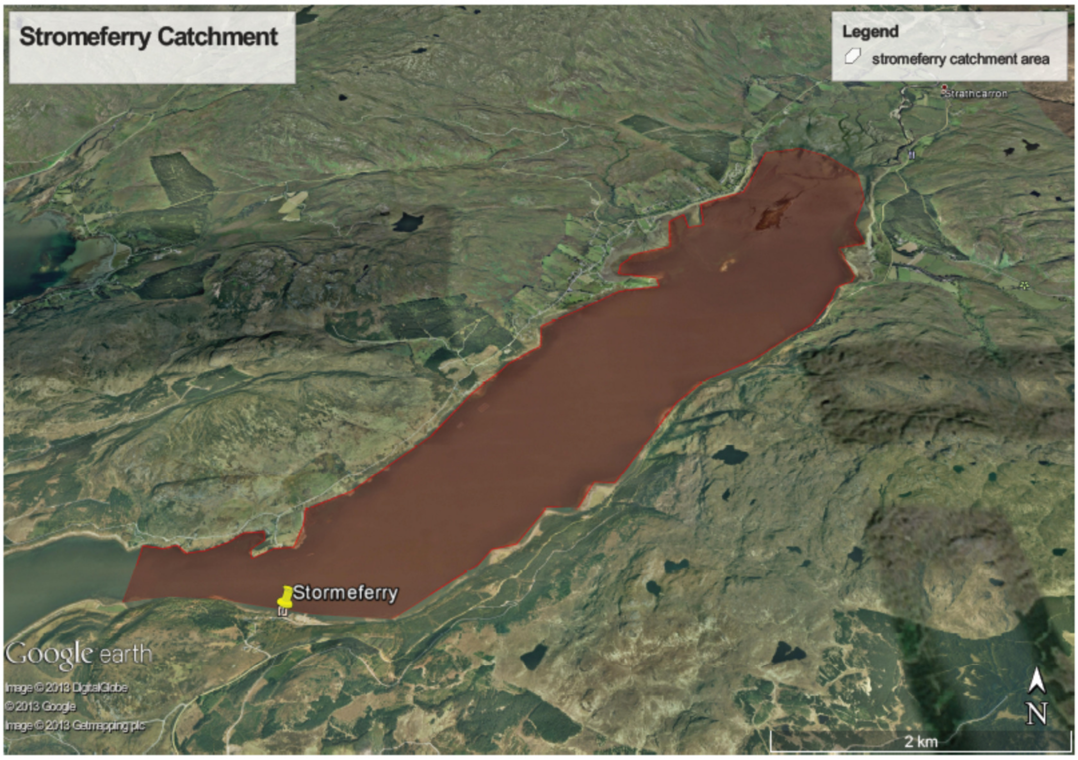
V_1=Velocity through the tidal bridge

$\rho A_1 V_1 = \rho A_2 V_2$

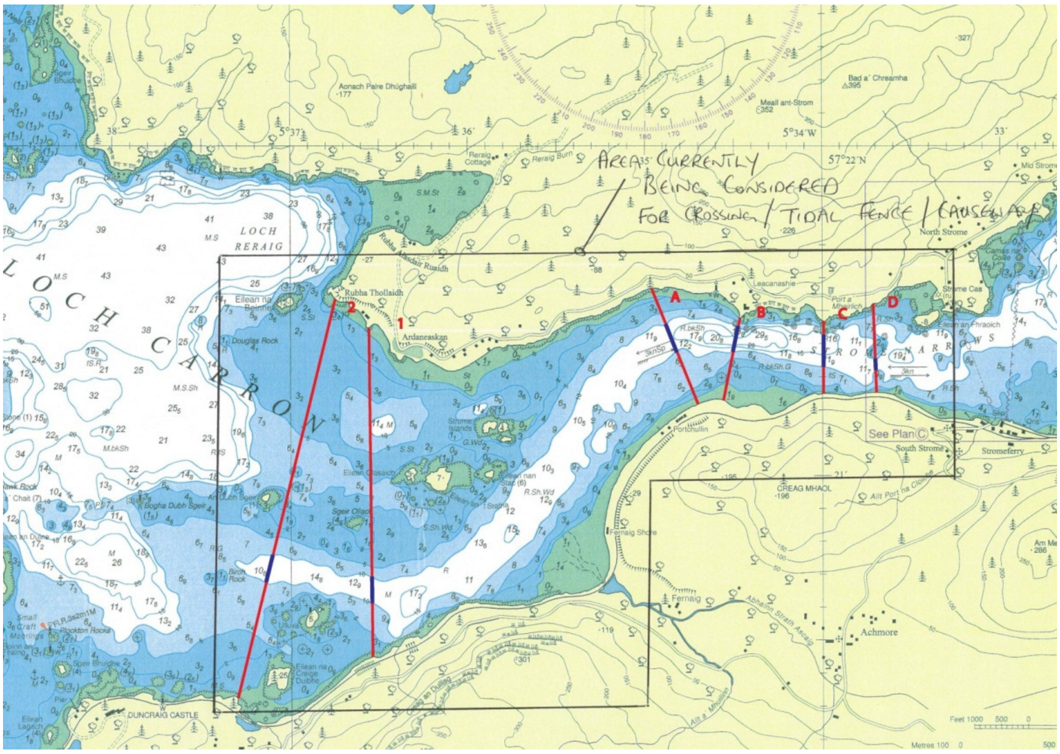
1025 x 220 x16 x 1.5 = 1025 x 110 x16 x V_2

V_2 = 3m/s

APPENDIX C STROMEFERRY CATCHMENT AREA



APPENDIX D STROMEFERRY CROSSING OPTIONS



APPENDIX D UNITED KINGDOM PROPOSED TIDAL GENERATION

Scheme	Mean tide Range (M)	Basin Area km^2	Capacity	Approx. Annual Output (TWh)	Annual Plant Load Factor
Severn	7.0	520	8640	17.0	0.22
Mersey	6.5	61	700	1.5	0.24
Wyre	6.0	5.8	47	0.09	0.22
Conwy	5.2	5.5	33	0.06	0.21