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TIDAL STREAM ENERGY
RESOURCE AND TECHNOLOGY SUMMARY REPORT

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1 EXECUTIVE SUMMARY

The UK has a significant domestic Tidal Stream Resource, representing around half of the European resource and around 10–15% of the *known* global resource. There is around 12 TWh/yr of UK Tidal Stream Resource that could be *economically* exploited. Utilisation of this Economically Extractable UK Resource would require about 3000 MW of installed capacity and represent over 3% of UK electricity demand. This suggests that the development of a UK tidal stream industry, through both technology and project development, would contribute meaningfully to UK electricity demand, and place the UK in a strong position to export that industry to other countries.

Black & Veatch (B&V) were engaged by the Carbon Trust to perform a 'Resource Assessment' and a series of 'Technology Assessments' as part of the 'Tidal Stream Work Package' component of the Marine Energy Challenge.

B&V has estimated the UK tidal stream Technically Extractable Resource to be 18 TWh/yr. There remains some uncertainty in this estimate (calculated to be approximately ±30%) due to uncertainty in the total tidal stream energy resource, and the fraction of that total resource that may be extracted without economic or environmental impact. This analysis indicates that the UK Technically Extractable Resource represents around 5% of UK electricity demand and this, despite the remaining uncertainty in the resource, suggests that tidal stream can contribute meaningfully to UK electricity demand if the technologies can become economic.

Of the total Technically Extractable Resource, about 63% is at sites with depths greater than 40m, 30% at sites with depths 30–40m, and there is limited resource in shallow (<30m depth) sites. Approximately 50% of the UK resource is in deep (>40m) sites with relatively high velocities. This resource distribution suggests that UK technology development should concentrate on devices suitable for sites with depths greater than 40m, with the highest focus on devices that are suitable for deep sites with high velocities. There is also merit in developing devices that are suitable for the 30–40m depth range, especially where these may be capable of deployment into greater depths in the future. Although there is a reasonable resource at low speed sites (with mean spring peak velocity (V_{msp}) less than 2.5 m/s), it may be more difficult for devices to extract this resource economically, and there appears to be little merit in focussing on devices only suitable for sites of depth <30m.

After analysing the different device types and configurations in conjunction with the results of the Resource Assessment, B&V concluded that the best prospects for the extensive deployment of cost-competitive tidal stream energy devices lie in turbine devices that are suitable for deployment in sites of depth > 30m and V_{msp} > 2.5 m/s. This analysis also showed that there was not a major difference in the economics of the horizontal or vertical axis turbine configurations, and both have a variety of advantages and disadvantages.

Technology assessments estimated the capital costs, operation and maintenance costs, and the energy production for two different types of horizontal axis turbine (located in two baseline sites with different water depths). A value engineering study explored the potential for performance improvement and cost reduction for the two turbine types. This produced baseline costs and performance figures for the two turbine types at the specific baseline site conditions. B&V developed a numerical model to allow the scaling of costs and performance for the full range of site conditions, and to optimise the rated velocity of each turbine at each new site condition. This analysis resulted in estimates of the energy generation cost for the site conditions present in the UK Extractable Resource. Although tidal stream farm deployment may occur simultaneously in a range of site conditions, the learning curve analysis had to assume a particular order of exploitation to produce an estimate of the energy generation costs with full deployment of the UK Extractable Resource, and a conservative view was taken of this order of exploitation.

Tidal stream technologies will require some early technology support (such as the recently announced Wave and Tidal Stream Energy Demonstration Scheme) in order to secure the first installations of relatively small tidal stream farms. The first large-scale tidal stream farms (~50 MW), with anticipated energy generation costs of around 7 p/kWh (assuming 8% discount rate and medium velocity sites) will also need further support over that offered by the Renewables Obligation (RO). However, the level of extra support required over the RO is expected to reduce to zero after around 1000 MW of installed capacity as energy generation costs reduce to about 5 p/kWh; this is similar to the level of extra support required for the initial UK off-shore wind farms. Support costs could be reduced by accelerating large-scale farm deployment in the higher velocity sites. Figure 4.1, and Figure 4.2, and Figure 4.3 show that tidal stream technologies can become competitive with other renewable energy technologies and, once extensive deployment and learning rates have been taken into account, can be supported purely by the RO in the higher velocity sites. Energy generation costs of around 3 p/kWh may be obtainable at the highest velocity sites, and thus tidal stream could become competitive with wholesale electricity prices.

2 SCOPE AND BACKGROUND

Black & Veatch (B&V) were engaged by the Carbon Trust to perform a 'Resource Assessment' and a series of 'Technology Assessments' as part of the 'Tidal Stream Work Package' component of the Marine Energy Challenge. This approach was used as there were a limited number of tidal stream developer responses to the Official Journal of the European Communities (OJEC) tender process, and hence it was not possible to work directly with device developers (in contrast to the approach for wave energy within the MEC).

The Resource Assessment was to take the form of a literature review of the UK and European tidal stream and marine current resource, as well as other information on the global resource. The resource was to be estimated for the UK, Europe, and globally, split into different types of site (e.g. high/medium velocity, shallow/deep water). Given the information sources available, it was anticipated that the tidal stream energy resource estimates would be more accurate for the UK and Europe than globally.

The Resource Assessment was performed in two phases. The first report entitled 'UK, Europe and Global Tidal Stream Energy Resource Assessment' (Revision 3, dated 20/12/2004) was issued into the public domain via the Carbon Trust website and other organisations at the end of 2004. The second report entitled 'Phase II UK Tidal Stream Energy Resource Assessment' (Revision 2, dated 15/07/2005) was issued into the public domain via the Carbon Trust website during July 2005.

In conjunction with the Resource Assessment a series of Technology Assessments were to be prepared on a number of example tidal stream devices using public-domain information or information from 'example device' developers where this was made available. The four 'example device' types considered were:

- Horizontal Axis Turbines
- Vertical Axis Turbines
- Oscillating Hydrofoil Devices
- Venturi Devices

The designs were to be primarily considered in their standard seabed-standing and un-shrouded configuration, although a number of other alternative configurations were to be considered, as detailed below:

- Seabed-standing and Shrouded
- Floating
- Floating and Shrouded

The Technology Assessments were to initially consider each example device under a set of universal baseline site conditions to enable a comparison of cost, performance and unit energy generation cost (p/kWh). This analysis was then to be extended by considering the energy generation costs for certain devices for various site conditions.

The Technology Assessments were intended to allow judgements to be formed on the present range of energy generation costs for tidal stream devices, and their suitability for different types of site.

The output of the Resource Assessment, together with the Technology Assessments, was intended to allow estimates of the size of the technical resource for each type of site and each type of device. Hence an opinion could be formed on the total size of the tidal stream energy market, and the potential range of future energy costs for tidal stream devices based on large-scale deployment.

This opinion was intended to help inform the Carbon Trust (and potentially other interested parties) as to whether the tidal stream sector had the potential to become cost competitive with other forms of electricity generation. This 'Tidal Stream Resource and Technology Summary Report' draws together all the work from the Tidal Stream Work Package.

B&V and the Carbon Trust would like to publicly thank the technology developers, and Robert Gordon University, who contributed technical evidence to this study.

3 RESOURCE ASSESSMENT

3.1 Overview

Section 6 of the Phase I Resource Assessment (20/12/2004) described B&V's independent assessment of the UK tidal stream resource. The results of this assessment clearly showed that using only a Farm Method is no longer appropriate to determine the tidal stream resource. The Farm Method was an extraction methodology used by previous assessments where the extracted energy is purely dependent on the size of the device, its efficiency, and the packing density of the devices. Improvements in the extraction efficiency of devices, and in the understanding of device spacing requirements mean that Farm based models have the ability to predict over-extraction – i.e., to predict extraction of more energy from the resource than actually exists. B&V concluded that the Farm Method needs to be constrained by a Flux Method that takes this resource availability into account. The Flux Method is an extraction methodology independently developed by B&V and Robert Gordon University (RGU) where the extracted energy is purely dependent on the incoming kinetic energy flux across the front cross-sectional area of a flow channel. Based on RGU's initial work, the Phase I B&V 2004 model applied a Significant Impact Factor (SIF) to the total resource to develop an initial (single number) estimate for the UK Technically Extractable Resource for comparison with previous figures. The SIF is the percentage of the Total Resource that can be extracted without significant economic or environmental impact. The report stressed that the 20% figure used for the SIF was indicative and should be determined for each site individually. The UK Total Resource was estimated at ~110 TWh/yr and the resulting UK Technically Extractable Resource was ~22 TWh/yr representing around 6% of UK electricity demand and half of the European Technically Extractable Resource. The *known* non-European global Technically Extractable Resource was estimated to be ~120 TWh/yr. The report stressed that this initial estimate for the UK Technically Extractable Resource was expected to provide the upper limit which might well require downwards revision, and recommended that further work be performed on a selection of prominent sites to determine more appropriate SIF values. B&V noted that not all presently known sites were identified and quantified within the study since it used previous data sources as a primary input. However, a large proportion of the resource is located within a few well known locations so it was considered unlikely that highly significant sites had not been identified by the study. Therefore, the overall effect on the UK Technically Extractable Resource of any missing sites was expected to be relatively low.

The Phase II work concentrated on validating the input data (site widths, depths, and velocities) for the ten most important tidal stream sites, comparing the data used in Phase I with data from the Marine Energy Atlas and Admiralty Chart / Tidal Stream Atlas data. Potential new sites were also investigated. B&V and RGU also developed more detailed SIF estimates for the key sites.

The Marine Energy Atlas identifies many potential new sites but, as expected, many of these are small sites with low velocities. There are a number of potential new sites of reasonable size, but many have low velocities. The main areas identified that are of both reasonable size and velocity are located at Islay, Carmel Head, and the Isle of Wight.

The updated Phase II Technically Extractable Resource is 18 TWh/yr, a reduction of 20% from the Phase I result. The reduction is due to: the removal of two Pentland Firth sites, as a substantial portion of their energy flux is not independent from other sites; reductions in tidal stream velocities at various Pentland Firth and Channel Island sites; and reductions in the estimated SIF for the Channel Islands, Rathlin Island, and Mull of Galloway sites.

There remains uncertainty in the resource estimate (this uncertainty is calculated to be approximately ±30% for the total resource, although higher for the individual sites) which is a result of uncertainty in the total energy resource and uncertainty in the application of the SIF. Only detailed site measurements will clarify the former uncertainty, and only further detailed modelling of both potential environmental effects and different types of site will clarify the latter. These detailed measurements and modelling will be important for site developers.

This analysis indicates that the UK tidal stream Technically Extractable Resource represents around 5% of UK electricity demand and this, despite the remaining uncertainty in the resource estimate, suggests that (if the technologies can become economic) the tidal stream resource can contribute meaningfully to UK electricity demand.

3.2 Distribution of the UK Technically Extractable Resource

The distribution of the UK Technically Extractable Resource with respect to depth and V_{msp} is summarised in Table 3.1.

V_{msp} (Mean Spring Peak Velocity) is tidal flow velocity taken at 5m below the surface and is one of the most often quoted parameters for a tidal stream site. When used in combination with other parameters it can be used to define the varying velocity at a site which defines the available energy – see the Resource Assessments for more details.

Key resource areas are highlighted:

🟥 Red: >20% of total resource

🟧 Orange: 10–20% of total resource

	B&V 2005 Extractable Resource Distribution by depth / velocity (%)					
Depth Range (m)	**V_{msp} Velocity Range (m/s)**					**Total**
	<2.5	**2.5–3.5**	**3.5–4.5**	**4.5–5.5**	**>5.5**	
<25	0.2	3.4	0.9	0.0	0.0	4.4
25–30	0.1	2.3	0.0	0.0	0.0	2.5
30–40	8.8	**18**	3.5	0.0	0.0	30
>40	**11**	3.3	**11**	**10**	**28**	63
Total	20	27	15	10	28	100

Table 3.1 – B&V 2005 Technically Extractable Resource Distribution by depth / velocity

Deep sites (>40m depth) represent some 63% of the UK resource, and sites of depth 30–40m represent 30% of the UK resource. There is limited UK resource in shallow (<30m depth) sites.

It is important to note that approximately 20% of the UK resource is within sites of depth 30–40m that have V_{msp} between 2.5–4.5 m/s. This site range has often been considered to be the most (economically) attractive type of site for near term developments using seabed-standing (e.g. monopile) devices; current velocities are not too high, the water is not so deep as to prevent realistic installation but deep enough to allow a reasonably large device size.

It is also important to note that approximately 50% of the UK resource is within deep (>40m) sites that have V_{msp} >3.5 m/s, and that nearly 30% of the UK resource is within the Pentland Skerries site with V_{msp} >5.5 m/s. These sites are only suited to device designs that are capable of being installed and operated in water depths greater than 40m.

3.3 Conclusions on the Impact of the UK Resource on UK Technology Development

The UK Technically Extractable Resource is only 18 TWh/yr, or 5% of the UK electricity demand, and therefore it will be necessary to exploit the key areas of the tidal stream resource to make a meaningful contribution to meeting the UK energy demand.

The resource distribution detailed in Table 3.1 suggests that UK technology development should be concentrated on devices that are suitable for sites of depth >40m, with the highest focus on devices that are suitable for deep sites with high velocities. There is also merit in developing devices that are suitable for the 30–40m depth range, especially where these may be capable of deployment into greater depths in the future. Although there is a reasonable resource at low speed sites (V_{msp} < 2.5 m/s), it may be more difficult for devices to extract this economically. There appears to be little merit in focussing UK technology development on devices that are only suitable for sites of depth <30m.

It should be noted that UK technology developers may also be interested in the global tidal stream technology market, where the resource distribution may be very different from that in the UK.

4 TECHNOLOGY ASSESSMENT

4.1 Overview

In conjunction with the Resource Assessment a series of Technology Assessments were prepared on a number of example tidal stream devices using public-domain information or information from ‘example device’ developers where this was made available. The four ‘example device’ types considered were:

- Horizontal Axis Turbines
- Vertical Axis Turbines
- Oscillating Hydrofoil Devices
- Venturi Devices

The designs were primarily considered in their standard seabed-standing and un-shrouded configuration although a number of other alternative configurations were considered, including:

- Seabed-standing and Shrouded
- Floating
- Floating and Shrouded

The Technology Assessments initially considered each example device under a set of universal baseline site conditions to enable a comparison of cost, performance, and unit energy generation cost (p/kWh).

The results of the initial Technology Assessments were considered in conjunction with the results of the Resource Assessment. This analysis showed that the best prospects for the extensive deployment of cost-competitive tidal stream energy devices lay in turbine devices that were suitable for deployment in sites of depth > 30m and $V_{msp} > 2.5$ m/s.

This analysis also showed that there was not a major difference in the economics of the horizontal or vertical axis turbine configurations, and both have a variety of advantages and disadvantages.

In order to develop an assessment of the potential range of future energy costs for tidal stream devices based on extensive deployment, it was decided to conduct a more detailed analysis on horizontal axis turbines because:

- Horizontal axis tidal stream turbines are generally more developed than vertical axis tidal stream turbines
- More information was available to the study for horizontal axis tidal stream turbines
- Wind industry trends may be more applicable for horizontal axis turbines

The Resource Assessment shows that sites of depth > 40m form a significant proportion of the UK tidal stream resource. It was therefore considered necessary to analyse types of horizontal axis turbine that are deployable at such sites, e.g., floating turbines. There is also an important resource at depths of 30–40m, and seabed-standing turbines were therefore also analysed. This resulted in two turbine types in the more detailed analysis:

- Floating turbines in sites of depth > 40m
- Seabed-standing turbines in sites of depth 30–40m

It should be noted that the DTI 2001 study entitled ‘The Commercial Prospects for Tidal Stream Power’, prepared by Binnie Black & Veatch in association with IT Power Ltd., considered an example of the seabed-standing turbine type (MCT’s ‘Seaflow’ design) that was under development at that time, and which continues to be further developed. The 2001 study concluded that unit energy generation costs of 4–6 p/kWh could be expected for large-scale (30 MW) farms at a particular set of site conditions ($V_{msp} = 3$ m/s and 30m water depth). These 2001 study results are in broad agreement with this present study which considers two turbine types, deployment of those turbines within the full range of UK site conditions, and the likely effect of extensive deployment on the long-term costs.

4.2 Energy Costs for Extensive Deployment of Horizontal Axis Tidal Stream Turbines

The Technology Assessments estimated the capital costs, operation and maintenance costs, and the energy production for each turbine type for a specific set of baseline site conditions (with different water depths for each turbine type).

B&V then performed a detailed cost analysis and value engineering study to explore the potential for performance improvement and cost reduction for the two turbine types. This resulted in baseline costs and performance figures for the two turbines at the specific baseline site conditions.

To estimate the potential range of future energy costs for tidal stream devices based on extensive deployment, B&V developed a numerical model to calculate costs and performance figures for the variety of site depths and velocities that comprise the UK Technically Extractable Resource. This calculation also optimised the rated velocity of the turbines at each site to minimise energy costs. The validity of these results is largely dependent on the correct estimation of the scaling of capital costs as the site conditions, and parameters, such as the rated velocity, are varied. Detailed analytical and empirical analyses were therefore undertaken to estimate these scaling parameters for the key cost items.

This analysis resulted in estimates of the energy generation cost for the site conditions present in the UK Resource.

B&V then applied learning curve reductions to the energy generation costs obtained from the above analysis. Although tidal stream farm deployment may occur simultaneously in a range of site conditions, the learning curve analysis had to assume a particular order of exploitation to produce an estimate of the energy generation costs with full deployment of the UK Extractable Resource. A relatively conservative view of this order of exploitation was taken, as outlined below:

- The 30–40m depth sites are exploited first in medium velocity sites ($V_{msp} = 2.5–3.5$ m/s), followed by the higher velocity sites ($V_{msp} = 3.5–4.5$ m/s), and finally in the low velocity sites ($V_{msp} < 2.5$ m/s)
- The deeper sites (>40m depth) are exploited first within the medium velocity sites ($V_{msp} = 2.5–3.5$ m/s), followed by the higher velocity sites ($V_{msp} = 3.5–4.5$ m/s, $V_{msp} = 4.5–5.5$ m/s and $V_{msp} > 5.5$ m/s), and finally within the low velocity sites ($V_{msp} < 2.5$ m/s)

This analysis results in a series of resource-cost figures for the UK Extractable Tidal Stream Resource.

A highly simplified representation of the resource-cost curve derived from this analysis is shown in Figure 4.1 and Figure 4.2; these curves show the energy generation costs for the full exploitation of particular resource areas in the same development progression order as detailed above. A possible chronological resource-cost curve (utilising the same learning curve analysis) is in Figure 4.3; this assumes a more likely development progression where particular resource areas are developed at the same time rather than sequentially as detailed above.

It needs to be borne in mind that the energy generation costs shown are *average* figures for the particular elements of the UK Extractable Resource. The first large-scale tidal stream farms have an anticipated energy cost of ~7 p/kWh.

The rise in the energy cost towards the right-hand side of Figure 4.1 and Figure 4.2 represents the fact that at this point the exploitation becomes based on significantly lower velocity sites, and hence significantly more expensive.

The error bands are intended to represent the uncertainties that are naturally present within the costs of a technology that is not yet deployed at full-scale, and the variation in learning rates that may occur for the different technologies.

For clarity of presentation, the error bands associated with the resource estimate are not shown, but the error band is approximately ±30%, as discussed in Section 3.1.

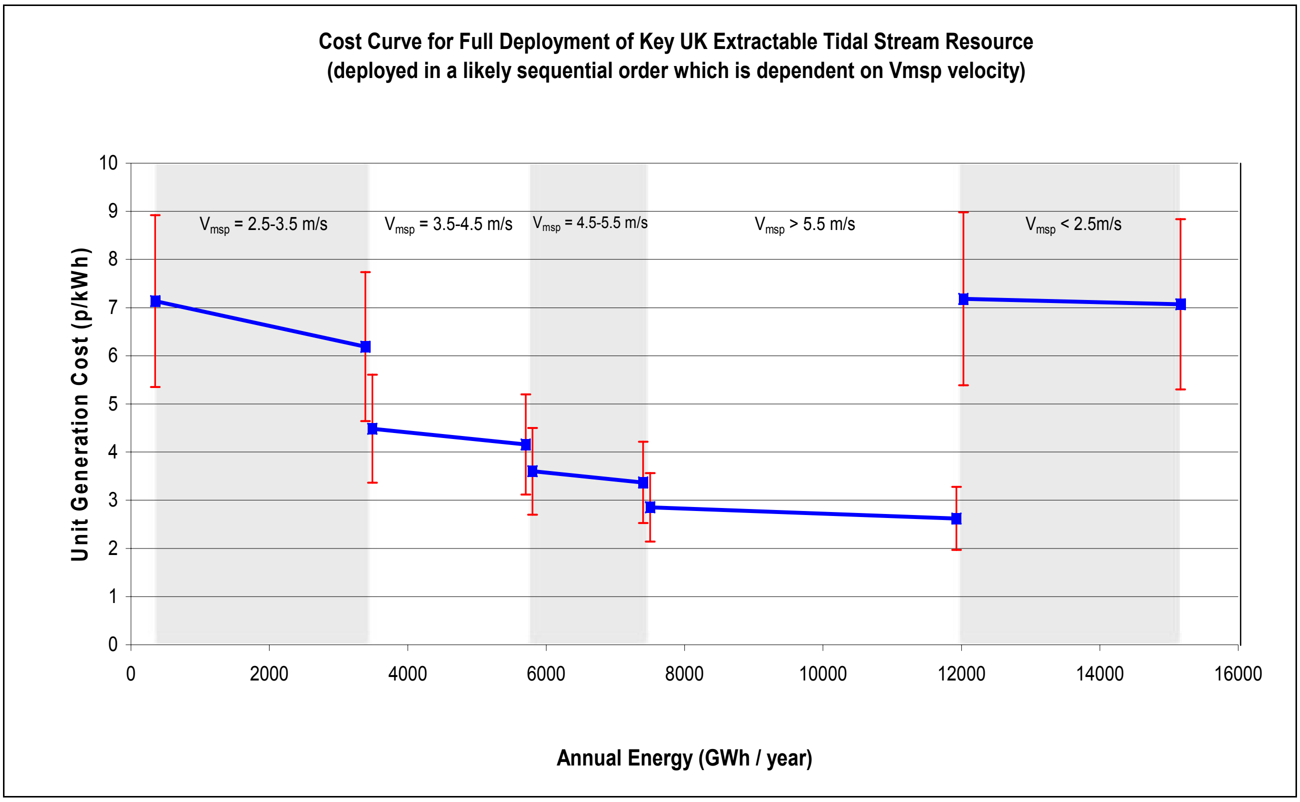

Figure 4.1 – Sequential Cost Curve (p/kWh) for Key UK Tidal Stream Resource (GWh/yr) (8% discount rate)

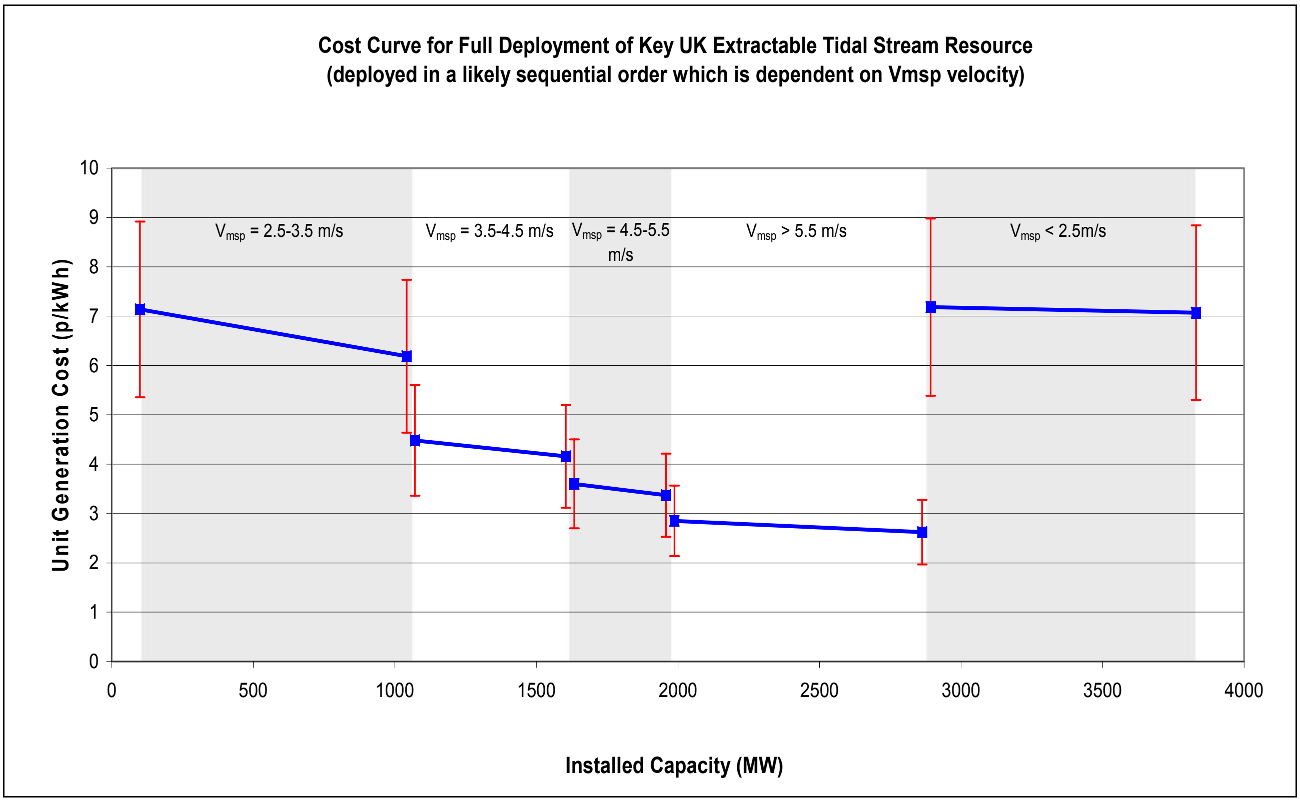

Figure 4.2 – Sequential Cost Curve (p/kWh) for Key UK Tidal Stream Resource ($MW_{installed}$) (8% discount rate)

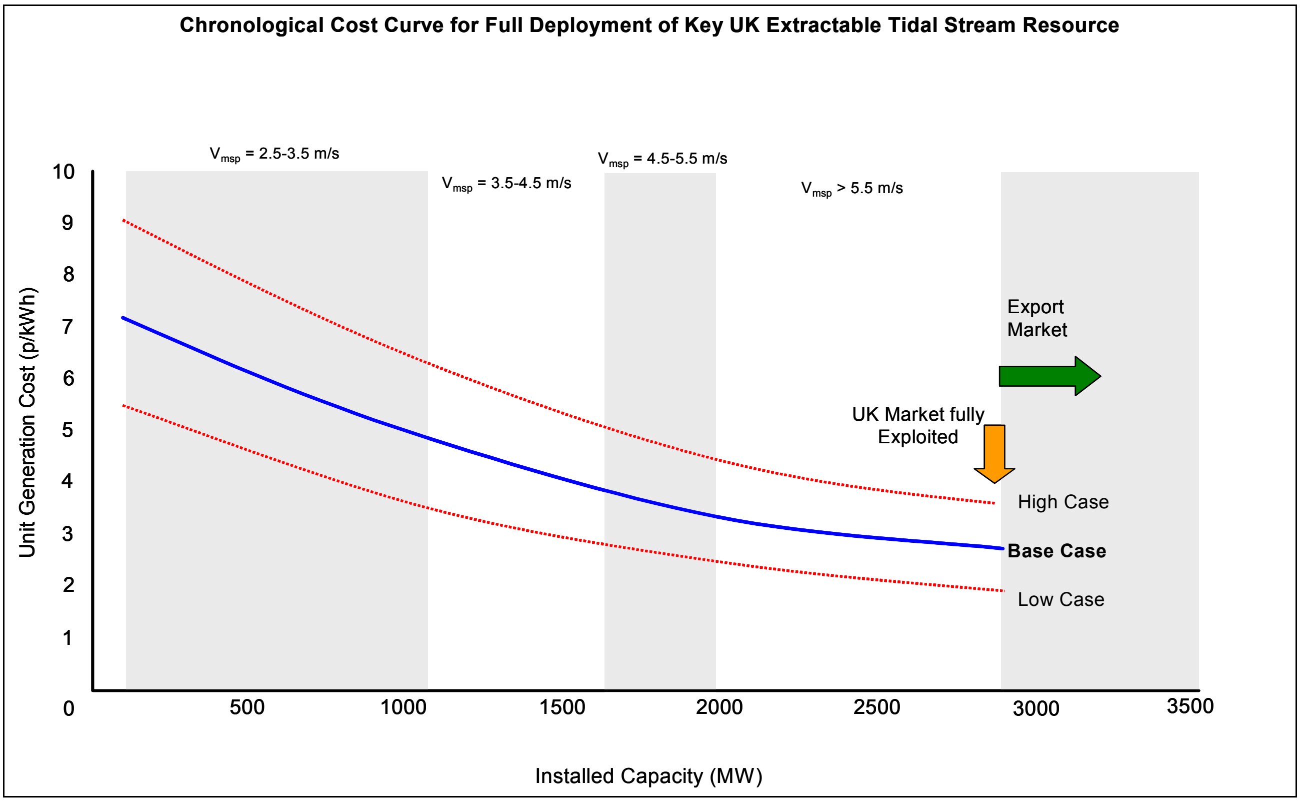

Figure 4.3 – Chronological Resource-Cost Curve for Key UK Tidal Stream Resource ($MW_{installed}$) (8% discount rate)

4.3 Discussion

Figure 4.1, Figure 4.2, and Figure 4.3 show that tidal stream technologies will require some early technology support (such as the recently announced Wave and Tidal Stream Energy Demonstration Scheme) to ensure the first installations of relatively small tidal stream farms.

These figures show that the first large-scale tidal stream farms, with an anticipated energy generation cost of ~7 p/kWh (assuming 8% discount rate and installation in medium velocity sites), will also need further support over that offered by the Renewables Obligation (RO) .

However, these figures also show that tidal stream technologies can become competitive with other renewable energy technologies and, once extensive deployment and learning rates have been taken into account, can be supported purely by the RO in the higher velocity sites. The level of extra support required (over the RO) is expected to reduce to zero after around 1000 MW of installed capacity as energy generation costs reduce to ~5 p/kWh; this is similar to the level of extra support required for the initial UK off-shore wind farms. It should be noted that these figures are strongly dependent on the types of sites in which initial installations occur, and the quoted figures assume installation in the order outlined in Section 4.2. Support costs could therefore be reduced by accelerating large-scale tidal stream farm deployment in the higher velocity sites.

It is also evident from Figures 4.1–4.2 that energy generation costs of around 3 p/kWh may be obtainable at the highest velocity sites, and thus tidal stream could become competitive with wholesale electricity prices in the future.

5 CONCLUSIONS

There is around 12 TWh/yr of UK tidal stream resource that could be economically exploited according to this combined Resource and Technology Assessment. This Economically Extractable UK resource represents over 3% of UK electricity demand, and would require about 3000 MW of installed capacity. Much of the remaining ~6 TWh/yr of the UK Technically Extractable Resource is likely to be uneconomic according to this analysis, although ~3 TWh/yr could be economic in the long-term under a high electricity price and low cost (high learning rate) scenario.

The UK has a domestic tidal stream resource that represents around half of the European resource, and around 10–15% of the *known* global resource. This significant resource, in combination with the economic analysis, suggests that the development of a UK tidal stream industry (through both technology and project development) would contribute meaningfully to UK electricity demand, and place the UK in a strong position to export that industry to other countries which have a tidal stream resource but may not be capable (for various reasons) of creating their own industry.