PHASE II
UK TIDAL STREAM ENERGY
RESOURCE ASSESSMENT

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1 EXECUTIVE SUMMARY

Black and Veatch (B&V) were engaged by the Carbon Trust to perform a ‘tidal stream resource assessment’ as part of the ‘Tidal Stream Work Package’ component of the Marine Energy Challenge.

B&V’s Phase I Report clearly showed that the use of only a Farm Method is no longer appropriate to determine the tidal stream resource. 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 exists originally. The result is that the Farm Method needs to be constrained by a Flux Method that takes this resource availability into account. Based on initial work by RGU, the Phase I B&V 2004 model applied a 20% SIF (Significant Impact Factor) to the total resource to develop an initial (single number) estimate for the Technically Extractable UK resource for comparison with previous figures. The report stressed that the chosen figure for the SIF was indicative and should be determined for each site individually. The UK Total Resource was estimated at ~110 TWh/y; the resulting UK Technically Extractable Resource was ~22 TWh/y representing around 6% of UK electricity demand and half of the European Technically Extractable Resource. The report also stressed that this initial estimate for the Technically Extractable Resource was expected to provide the upper limit and 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 this 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 this study. Therefore, the overall effect on the UK resource of any missing sites was expected to be relatively low.

This Phase II Report therefore 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. Black & Veatch 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 again many have low velocities. The main areas identified that are of both reasonable size and reasonable velocity (>2.5 m/s) are located at Islay, Carmel Head, and the Isle of Wight.

The updated Phase II Technically Extractable Resource is 18 TWh/y, a reduction of 20% of 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 Island, Rathlin Island, and Mull of Galloway sites.

Approximately 20% of this UK resource is within sites of depth 30–40m that have $V_{misp}$ between 2.5–4.5 m/s. These are probably the sites most (economically) suited to near term developments that use seabed-standing devices (using for example monopile designs). Approximately 50% of the UK resource is within deep (>40m) sites that have $V_{misp} >3.5$ m/s; these are only suited to device designs that are capable of being installed and operated in water depths > 40m.

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 sites will clarify the latter. These detailed measurements and modelling will be important for site developers.

This updated analysis indicates that the UK tidal stream Technically Extractable Resource represents around 5% of UK electricity demand, and despite the remaining uncertainty in the resource estimate, this suggests that tidal stream can contribute meaningfully to UK electricity demand.
GLOSSARY OF TERMS

Available Resource (TWh/y) – Calculated by use of the Flux Method, this is the total energy over a year that could be extracted from a flow without causing significant changes to flow momentum, or significant environmental impact to the site or other areas. It is equal to Total Resource multiplied by Significant Impact Factor.

Extractable Resource (TWh/y) – Total energy over a year that could be produced in theory using the Farm Method.

The Farm Method – Extraction methodology based on developing an array of tidal stream devices that each extract an equal amount of energy from the incoming flux. The number of devices and hence the extracted energy is purely dependent on the size of the device, its efficiency, and the packing density within the plan area.

The Flux Method – Extraction methodology based on the use of only the incoming kinetic energy flux across the front cross-sectional area of a flow channel. This is independent of the device type, efficiency and packing density, taking only the kinetic energy flowing in the channel into account.

MEA – Marine Energy Atlas

Rated velocity factor – \( \frac{V_{\text{rated}}}{V_{\text{msp}}} \). Rated velocity factor is ratio of the rated velocity of a tidal stream device to the mean spring peak velocity of the flow (71% in the analysis within the Phase I Report).

Ratio of 1st to 2nd tide (flood to ebb) – Mean Average peak velocity \( V_{\text{max}} \) for the 1st flood tide (flood) / Mean Average peak velocity \( V_{\text{max}} \) for the 2nd ebb tide (ebb).

RGU – Robert Gordon University

Significant Impact Factor (SIF) (%) – The percentage of the Total Resource that can be extracted without significant economic or environmental effect, to give the Available Resource. This is site dependent.

Total Resource (TWh/y) – Total energy over a year that exists within a flow of water, using the Flux Method.

\( V_{\text{mnp}} \) (m/s) – Mean neap peak velocity as defined by the Admiralty charts for a particular site, 5 m below the surface.

\( V_{\text{msp}} \) (m/s) – Mean spring peak velocity as defined by the Admiralty charts for a particular site, 5 m below surface.

\( V_{\text{rated}} \) (m/s) – Rated velocity of tidal stream device. Rated velocity is the velocity at which the device reaches maximum (rated) output (for this report an average of 71% of \( V_{\text{msp}} \) has been used).
2 **SCOPE AND BACKGROUND**

Black & Veatch (B&V) were engaged by the Carbon Trust, as part of the Marine Energy Challenge, to perform a ‘resource assessment’ as part of the ‘Tidal Stream Work Package’. Phase I of this assessment was completed during 2004, and a final (revision 3) Phase I Resource Report was issued on 20th December 2004 entitled: ‘UK, Europe and Global Tidal Stream Energy Resource Assessment’. The reader is referred to this report for full details of the work completed, and a summary is given below.

Section 5 of the Phase I Report provides an overview of the literature review that was originally intended to form the main basis for the assessment of the UK, European, and global tidal stream resource. This review resulted in B&V developing the Flux Method of resource analysis, in addition to the Farm Method.

Section 6 of the Phase I Report outlines the (Phase I) independent assessment of the UK’s tidal stream resource that was made by B&V. A comparison of the methodology, and the result of this assessment, was made with the other assessments found during the literature review. It was clear that the use of only a Farm Method is no longer appropriate. Improvements in the extraction efficiency of devices, and in the understanding of device spacing requirements, mean that the Farm Method has the ability to predict over-extraction i.e., to predict ‘extraction’ of more energy from the resource than exists originally. The result is that the Farm Method needs to be constrained by a Flux Method that takes this resource availability into account. Recent studies by Robert Gordon University (RGU) suggest that most UK sites will be constrained so that only a fraction of the total resource is available for extraction. B&V have defined this constraint as the Significant Impact Factor (SIF). Based on the work by RGU, the B&V 2004 model applied a 20% SIF to the total resource to develop an initial (single number) estimate for the technically ‘Available and Extractable’ UK Resource. It was stated that this initial estimate was expected to be revised (slightly) downwards in future work. It was noted that this estimate of a 20% SIF for all sites is intended to account for environmental issues that are likely to depend on the energy extraction at a site, but does not represent a site by site assessment of issues such as site designations or competing sea uses, nor for other practical extraction considerations such as project economics or grid access.

Section 7 of the Phase I Report estimated the UK Total Resource at ~110 TWh/y; the resulting UK Technically Extractable Resource is ~22 TWh/y. It was noted that the source data for the B&V 2004 estimate is a combination of the data used in two major previous studies that gave comparable values of 58 TWh/y and 31 TWh/y for the Technically Extractable Resource. Section 8 of the Phase I Report estimated the non-UK European Technically Extractable Resource as ~17 TWh/y. Section 9 of the Phase I Report estimated the non-European global Total Resource as 600 TWh/y although there was a high degree of uncertainty associated with this estimation; the resulting Technically Extractable Resource was ~120 TWh/y.

Section 10 of the Phase I Report concluded that the UK has a significant Technically Extractable Resource (around 6% of UK electricity demand), and this resource represents around half of the European Technically Extractable Resource. Despite the large uncertainties for the global Resource estimates, it can probably be concluded that the UK resource is a significant portion (10-15%) of the known global Resource. Much of the UK resource is concentrated in the Pentland Firth and the Channel Islands, and most of this resource is found at depths greater than 40 m. It was therefore recommended that further work be carried out to develop more detailed SIF values for various types of site, and for the most important sites in terms of their contribution to the Extractable Resource. Since the results of the B&V 2004 analysis were dependent on the site data in previous reports, it was also recommended that any update to the model should use updated site data from either the Marine Energy Atlas or Admiralty Charts.

On the basis of the Phase I Report, the scope for the Phase II was agreed in December 2004. It was agreed that the UK resource would be analysed to identify the most important sites, and that the input data required by the B&V model for these sites would be validated by comparison to the Marine Energy Atlas and Admiralty Chart data. It was also agreed that B&V would work with RGU to develop more detailed SIF estimates for these sites. It was later agreed that RGU would carry out some additional ‘flux’ modelling of the Channel Islands resource through the further development of a new modelling method that they have recently applied to the Pentland Firth in work for the Scottish Executive. This work by RGU will provide another comparative check for the Pentland Firth and Channel Islands resources that make up a large majority of the UK resource.
3 **THE SIGNIFICANT IMPACT FACTOR (SIF)**

An explanation of the Farm Method and the Flux Method has been given in the Phase I Report, and this section reminds the reader of the Significant Impact Factor (SIF) as it was discussed in that report.

The Flux Method results in a Total Resource value for each site, which is the product only of the time-varying (kinetic) power flux at a site and the cross-sectional area of the channel. There is clearly only a percentage of the total (kinetic and potential) energy in a site can be extracted without significant alteration to flow speed. Alteration to flow speed has an important effect on the economics of energy generation in addition to possible environmental impacts.

Robert Gordon University (RGU) have suggested that the percentage of this Total Resource value that is available for extraction will be dependent on the type of site. In channels where the flow is governed by a head difference at either end of the channel, and the flow cannot affect the tidal elevation in the bodies of water at either end, significant effects on the flow can be noted when this percentage (of the kinetic energy) is around 10%. Such areas would include many of the Orkney and Shetland channels (the behaviour of which is set by the tidal phase difference created across the channels by the islands themselves). Other modelling by RGU has suggested that up to 50% (kinetic energy) extraction could be possible in areas where the flow has more freedom within its elevation boundary conditions, without significant effects. Such areas would include the English Channel and sea lochs. It is important to note that these percentages are based on theoretical modelling results and these theoretical models have still to be validated against physical experiments.

B&V therefore defined a ‘Significant Impact Factor’ (SIF) in this Phase I report, representing the percentage of the total (kinetic energy) resource at a site that could be extracted without significant economic or environmental effects. It should be noted that the SIF is intended to account for environmental issues that are likely to depend on the energy extraction at a site, but does not represent a site by site assessment of issues such as site designations or competing sea uses, nor for other practical extraction considerations such as project economics or grid access.

The Available Resource is therefore defined as the product of the Total Resource and the Significant Impact Factor. The Available Resource is therefore the resource that is likely to be ‘technically available’ prior to imposition of more practical constraints.

The SIF is thought to vary across the different types of site, and there is a need to validate the RGU models so the Phase I Report made a preliminary, generalised estimate that the UK Available Resource is 20% of the UK Total Resource. This choice of an indicative average 20% SIF allows the development of an initial (single number) estimate for the Available UK resource that may be compared to previous studies. Further work to develop estimates for the Available Resource could focus on validating these RGU models and then applying the varying SIF to the different sites. This initial estimate will need revision as further understanding and knowledge is developed within the industry. At the time of the Phase I Report, B&V believed that the use of an indicative 20% SIF factor for all sites would result in an upper limit for the Available Resource.

Potential environmental impacts of tidal stream energy developments must be considered in the global context of climate change and the environmental disadvantages of other competing technologies. Any indicative SIF must be considered with this in mind – as public and scientific perception of climate change develops then attitudes to the environmental effects of renewable energy extraction are likely to be adjusted.

Since all sites are different, the SIF values developed in this report should not be considered to pre-judge the results of a full environmental impact assessment for any particular site, or set a precedent as to the anticipated result.
4 ANALYSIS OF THE UK RESOURCE

4.1 Findings of the Phase I Report

The UK resource identified in the Phase I Report is summarised below. The ‘total resource’ represents the result of the flux methodology before application of any SIF; the ‘extractable and available resource’ represents this resource after the application of the 20% estimate for the SIF (the resource is ‘extractable’ by the farm methodology).

<table>
<thead>
<tr>
<th>Depth Range (m)</th>
<th>B&amp;V 2004 Total Resource (GWh/y) (% in brackets)</th>
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<tr>
<td></td>
<td>Velocity Range (m/s)</td>
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<tr>
<td></td>
<td>&lt;2.5</td>
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<tr>
<td>&lt;25</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>(0.1)</td>
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<tr>
<td>25 – 30</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>(0.1)</td>
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<tr>
<td>30 – 40</td>
<td>865</td>
</tr>
<tr>
<td></td>
<td>(0.8)</td>
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<tr>
<td>&gt;40</td>
<td>2957</td>
</tr>
<tr>
<td></td>
<td>(2.7)</td>
</tr>
<tr>
<td>Total</td>
<td>4043</td>
</tr>
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<td>(3.7)</td>
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</table>

Table 4-1 – B&V 2004 UK Total Resource Distribution

<table>
<thead>
<tr>
<th>Depth Range (m)</th>
<th>B&amp;V 2004 Extractable &amp; Available Annual Energy (extractable limit is 20% of total resource) (GWh/y) (% in brackets)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Velocity Range (m/s)</td>
</tr>
<tr>
<td></td>
<td>&lt;2.5</td>
</tr>
<tr>
<td>&lt;25</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>(0.1)</td>
</tr>
<tr>
<td>25 – 30</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>(0.1)</td>
</tr>
<tr>
<td>30 – 40</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td>(0.8)</td>
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<tr>
<td>&gt;40</td>
<td>558</td>
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<td></td>
<td>(2.6)</td>
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<tr>
<td>Total</td>
<td>774</td>
</tr>
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<td>(3.5)</td>
</tr>
</tbody>
</table>

Table 4-2 – B&V 2004 UK Extractable and Available Resource Distribution
4.2 Key Sites within the UK Resource

In an ideal situation, Phase II would have validated all the input data required by the B&V model and developed more accurate estimates for the SIF for each UK site. However, time and budget precluded such an approach, and as the industry’s understanding of the SIF is still developing, a more simplistic and pragmatic approach was required.

The Phase I UK Resource has been analysed to identify the most important sites in terms of their contribution to the total resource so that the input data required by the B&V model for these sites could be validated by comparison to the Marine Energy Atlas and Admiralty Chart data, and so that more detailed SIF estimates for these sites could be developed. The UK resource at Phase I was made up of 57 individual sites, and these have initially been ranked in size to identify the sites that contain 80% of the UK’s total resource; the intention being that an increase in confidence in the total and available resource at these sites would lead to an increase in the overall level of confidence for both the total and available UK resource.

The full analysis of the contribution of each site to the Phase I estimate of the extractable and available resource is shown in Appendix 1, and a summary of the most important sites is shown in Table 4-3 below.

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Site Name</th>
<th>Contribution (%)</th>
<th>Cumulative (%)</th>
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<tbody>
<tr>
<td>1</td>
<td>Pentland Skerries</td>
<td>17.9</td>
<td>17.9</td>
</tr>
<tr>
<td>2</td>
<td>Stroma, P. Firth</td>
<td>12.7</td>
<td>30.6</td>
</tr>
<tr>
<td>3</td>
<td>Duncansby Head, P. Firth</td>
<td>9.3</td>
<td>39.9</td>
</tr>
<tr>
<td>4</td>
<td>Casquets, Channel Islands</td>
<td>7.6</td>
<td>47.5</td>
</tr>
<tr>
<td>5</td>
<td>S. Ronaldsay, P. Firth</td>
<td>7.0</td>
<td>54.4</td>
</tr>
<tr>
<td>6</td>
<td>Hoy, P. Firth</td>
<td>6.3</td>
<td>60.8</td>
</tr>
<tr>
<td>7</td>
<td>Race of Alderney, Ch. Is.</td>
<td>6.3</td>
<td>67.0</td>
</tr>
<tr>
<td>8</td>
<td>S. Ronaldsay, P. Skerries</td>
<td>5.3</td>
<td>72.3</td>
</tr>
<tr>
<td>9</td>
<td>Rathlin Island</td>
<td>4.0</td>
<td>76.2</td>
</tr>
<tr>
<td>10</td>
<td>Mull of Galloway</td>
<td>3.7</td>
<td>79.9</td>
</tr>
</tbody>
</table>

Table 4-3 – Phase I Sites with 80% of the total resource

It is clear that in Phase I, 80% of the total UK resource is contained in just 10 of the 57 sites, with over 70% of the resource in the Pentland Firth and the Channel Islands. The full analysis shows that there are many Phase I sites that are unimportant in terms of the total UK resource, and this can be clearly seen in Figure 4.1 below.

![Cumulative Contribution to UK Total Resource](image)
4.3 Validation of key B&V model input parameters

It has been discussed that the input parameters for the Phase I B&V model were taken from various literature sources, and therefore that these parameters would be reviewed in Phase II for the most important sites.

4.3.1 Methodology

The sites for validation of their input parameters have been identified above, and the input model parameters associated with these sites have been reviewed using the following methodology:

(a) Check if any Phase I sites are arranged such that double-counting of a flux resource can occur. This check is required to ensure that where several sites are close together (such as in the Pentland Firth) the flux from one site does not flow into another, and thereby result in double-counting of the flux resource.

(b) Identify data sources for review of the Phase I site depth, width, \( V_{mpw} \), \( V_{mpn} \), 1st / 2nd tide ratios, and then utilise these sources to review the Phase I input parameters.

(c) Review the likely Significant Impact Factor (SIF) for the different sites.

4.3.2 Double counting of flux across different sites

Many of the sites in the Pentland Firth are close together. There are several sites that are arranged directly across the flow streamlines (for instance Duncansby Head, Pentland Skerries, and S. Ronaldsay/Pentland Skerries) and in these cases it is likely that the flux is not double-counted (however much of the channel width is covered).

There are sites such as S. Ronaldsay/Pentland Firth that may create some double counting with other sites such as S. Ronaldsay/Pentland Skerries and this could potentially reduce the UK resource by around 5%.

There are also three sites (Pentland Skerries, Stroma, and Hoy) that are adjoining in the longitudinal direction of the general flow streamlines; it is likely that much of the flux within Pentland Skerries and Stoma has been double-counted in Phase I. It also appears at first sight that Hoy’s flux is also part of the Pentland Skerries / Stroma flux; however on closer inspection of the charts it seems likely that a substantial portion of Hoy’s flux is independent. If much of the Stroma flux were to be excluded then this could reduce the UK resource by up to 10%.

In Phase I the available resource associated with the Pentland Firth was 12.75 TWh/y (representing 58% of the UK resource), and the full removal of both S. Ronaldsay/Pentland Skerries and Stoma from that resource would remove 3.9 TWh/y from that resource resulting in a revised Pentland Firth available resource of 8.8 TWh/y.

No other major issues of flux double-counting were found in the review of the UK sites. It therefore seems possible that the UK resource may have been over-estimated in Phase I by up to 15% due to this flux double-counting issue.

It is clear that the sites used in Phase I for the Pentland Firth, taken from the literature search and developed in previous studies for use with the older farm methodology, cannot be easily used to derive an accurate estimation of the resource using the newer flux methodology. B&V therefore decided to review the parameters for these sites with a view to updating the resource for each of the original sites, but also with a view to calculating a new set of results for the Eastern or Western boundaries of the Pentland Firth without any reference to exact sites. This latter calculation was intended to then be compared to the recent work on the Pentland Firth that has been carried out by RGU for the Scottish Executive which uses a similar methodology.
4.3.3 Data sources for review of model input parameters

The following sources of tidal stream data were identified for consideration for reviewing the input parameters:

(a) Admiralty Charts and Tidal Stream Atlases
(b) Marine Energy Atlas (outputs of the POL UK grid tidal stream model)
(c) Current meter measurements from the National Archives
(d) Local port authority (sailing pilots) and tourist board information

After review of the availability of these sources it was decided to obtain updated Admiralty Charts and Tidal Stream Atlases for the relevant areas, and to cross-check the information obtained from these with that from the Marine Energy Atlas.

The Admiralty Charts were initially used to review the width and depth of the original Phase I sites, and the Tidal Stream Atlases were used to review the tidal stream parameters of \( V_{msp} \), \( V_{mnp} \), and 1st/2nd tide ratios. Data was then extracted from the Marine Energy Atlas for further comparison purposes. This review resulted in B&V 2005 model input parameters that can be directly compared to the Phase I parameters which were taken from the literature.

It should be noted that due to the relatively large grid size (1.8km) in the Marine Energy Atlas (MEA) it can be difficult to extract useful information for specific tidal stream sites within pre-defined boundaries. However, the MEA is useful for cross-checking any parameters where there appears to be a significant difference between the Phase I results and those obtained through the initial Phase II review process as outlined above.

This section only details the major changes for each parameter; the full comparative results are in Appendix 2. The major changes are given in the same order as the ranking of the sites in Table 4-3.

4.3.4 Phase II Input Parameters

4.3.4.1 Site Widths

In terms of site widths, the only major discrepancy found (when compared to the Phase I parameters) was for the Race of Alderney, where the width was actually increased from 3300m to 5000m to account for the actual shape of the site with respect to the nearest tidal stream data point.

4.3.4.2 Site Depths

In terms of site depths, there were more discrepancies between the Phase I data (taken from the literature) and the Phase II updated comparisons. The Phase II updated depths were calculated using an averaging process for the pre-defined sites. Whilst most sites were not substantially different, the following changes were noted:

(a) The depth for the Casquets site was decreased from 115m to 80m.
(b) The depth for the Race of Alderney site was increased from 33m to 39m.
(c) The depth for the Mull of Galloway site was decreased from 80m to 57m
(d) The depth for the Rathlin Island site was increased from 80m to 100m

It should be noted that the major changes to the Casquets, Mull of Galloway, and Rathlin Island site depths are in agreement with MEA results. It is thought that the reductions in depth at Casquets and Mull of Galloway are due to previous literature being based on maximum site depths rather than averages across the site width; the reason behind the increase in depth at Rathlin Island is not clear.
4.3.4.3 Tidal Stream Velocities

Discrepancies between the Phase I tidal stream velocity values and those derived in Phase II are more important than any discrepancies in depth or width, as the energy flux within a site is related to the cube of the velocity. In general the Phase II review using Tidal Stream Atlases has resulted in lower $V_{mp}$ and $V_{mnp}$ velocities than those used in Phase I, and this is thought to be related to the general use in the literature of absolute maximum velocities (i.e., the highest velocities that occur for a few minutes or hours per year) rather than $V_{mp}$ or $V_{mnp}$ velocities.

The comparative situation with respect to tidal stream velocities is not as clear-cut as with site widths and depths, and whilst in many cases the Phase II initial review results (using tidal stream atlases) are substantiated by the results from the MEA, in some cases the MEA results are substantially different from the Phase II initial results. This effect is especially noticeable for Pentland Skerries, S. Ronaldsay/Pentland Firth, and the Race of Alderney. It is believed that the results from the tidal stream atlases are more robust as they are generally of a higher resolution, and in many cases the MEA results for a site (average width 3.6km) require several 1.8km grid cells to be averaged to obtain the result, and the tidal streams outside the pre-defined site are generally significantly different.

Therefore the following major changes have been made to tidal stream velocities:

(a) Casquets site: $V_{mp}$ is reduced to 88% of Phase I value, and $V_{mnp}$ is reduced to 85% of Phase I value. However the ratio of the 1st/2nd tide is increased from 0.71 to 0.92; the net effect is a reduction in energy flux of only 13% from the Phase I value.

(b) S. Ronaldsay/Pentland Firth site: $V_{mp}$ is reduced to 87% of Phase I value, and $V_{mnp}$ is reduced to 92% of Phase I value. The net effect is a reduction in energy flux of 36% from the Phase I value.

(c) Hoy site: $V_{mp}$ is reduced to 85% of Phase I value, and $V_{mnp}$ is reduced to 88% of Phase I value. The net effect is a reduction in energy flux of 39% from the Phase I value.

(d) Race of Alderney site: $V_{mp}$ is reduced to 67% of Phase I value, and $V_{mnp}$ is reduced to 54% of Phase I value. This is a very significant change; the MEA shows velocities as high as the Phase I results but the tidal stream atlases clearly show that the highest velocities (that are thought to be those used in the literature and also those affecting the MEA result) are just outside the UK’s territorial waters. The net effect is a reduction in energy flux of 75% from the Phase I value, but it should be noted that this ‘lost resource’ probably exists within the French territorial waters that are extremely close to this site.

4.3.5 Significant Impact Factor (SIF) for the different sites

As discussed above, the industry’s understanding of the SIF is still developing, and in Phase II B&V reviewed the more recent work by RGU on the effects of energy extraction, and discussed with them their latest findings. The intention was to develop arguments that could allow the estimation of the SIF for different types of site, and to develop a more detailed estimation for a likely SIF for the key sites. RGU are continuing to develop models of energy extraction as part of the SUPERGEN program, and B&V believe that this report shows that there is a significant requirement for further detailed and targeted modelling.

4.3.5.1 Types of site with respect to SIF

During Phase I & II, five essentially different types of tidal stream site (with respect to SIF) were initially identified:

(a) Inter-island channels with ‘fixed’ head differences. The ‘fixed’ head difference is caused by a tidal phase lag between the two ends of the channel. In these channels the flow is broadly governed by the head difference at either end of the channel and the flow does not greatly affect the tidal elevation in the bodies of water at either end. Pentland Firth and other areas around the Orkneys and Shetlands are typical examples. In Phase I it was noted that energy extraction started to have significant effects on the flow at kinetic extraction rates of around 10% and therefore SIFs in the range 10–20% were thought likely.

(b) Open Sea sites with ‘fixed’ head differences. These are effectively similar to very wide channels without any side boundaries and therefore water is able to flow in/out of the site through these boundaries. It is believed that such sites would experience similar effects to wide channels, and therefore SIFs in the range 10–20% were
initially thought likely. Channel Island sites such as Casquets are typical examples, although with high extraction the Channel Island sites may behave similarly to sea lochs, and head differences may be affected by energy extraction.

(c) Headlands with ‘fixed’ head differences. The flow around headlands is generally very complex with shifting maximum tidal stream velocity locations; a typical example of this complexity can be seen in the flow around Portland Bill. These types of site are similar to open-sea sites with a side boundary. It is believed that such sites would experience similar effects to open-sea sites, and therefore SIFs in the range 10–20% were initially thought likely.

(d) Sea lochs with head differences determined by the energy extraction. Initial work by RGU has showed that energy extraction has little effect on such sites, as reducing the tidal stream velocity through energy extraction has a positive feedback on the head difference in a similar fashion to that experienced with a traditional barrage. It is therefore believed that SIFs of up to 50% could be possible for such sites. It should be noted that such sites contribute only a small fraction of the total UK resource.

(e) Resonant estuaries where the head differences are a result of complex (resonant) effects. Due to the complexity of such sites it is believed that the effects of energy extraction could be larger than for the other types of site, and given that such sites also tend to be more environmentally sensitive, SIFs of <10% were therefore anticipated.

It is therefore clear that the majority of the most important sites as outlined in Table 4-3 are of types (a) to (c) and were therefore initially expected to have SIFs in the range 10–20%; hence the use of 20% as the overall SIF factor in Phase I. Since all the most important sites are similar in nature, it was expected that the results for a theoretical study of Pentland Firth (representing the most important site) could be used to inform the estimated SIF for all the most important sites. RGU was therefore commissioned to perform some further investigation into the potential effects of different energy extraction regimes on tidal stream velocities for a (theoretical) Pentland Firth type site.

It should be noted that the work performed by RGU is based on a simple 1-D channel model of the Pentland Firth, with a fixed width and depth. It is also important to note that the model is simulating a series of steady-flow regimes which is obviously not the case in practice (as the flows will vary approximately sinusoidally), but such an approach does allow calculations to be performed from a series of snap-shots of the tidal cycle. Both RGU and B&V possess 2-D and 3-D tidal modelling capability which could be utilised at a later date to validate these initial results for the Pentland Firth and other important sites, but this level of detail is not appropriate at this stage.

4.3.5.2 Factors that could affect the SIF

Separately from the above work that was completed by RGU, B&V have analysed the requirements for energy extraction at different flow velocities such that a certain overall (kinetic) energy extraction occurs across a tidal cycle. Since devices are expected to have a rated velocity factor of c. 70%, the rated velocity for an average Pentland Firth site is expected to be the order of 3.5 m/s. Extraction devices such as turbines will have an efficiency curve across a range of flow velocities; however this efficiency can be close to constant (up to rated power) if turbines use variable speed / pitch control. In this situation the energy extraction as a percentage of the raw kinetic energy flux is also broadly constant up to rated power; however at flow velocities greater than the rated velocity the energy extraction as a percentage of the raw kinetic energy flux will reduce since the energy extraction of the turbines is limited but the kinetic energy of the tidal stream itself is still increasing. For a typical Pentland Firth site with a \( V_{\text{msp}} \) of ~5 m/s it can be calculated that in order to obtain an overall kinetic energy extraction of 20%, a rated (kinetic) energy extraction of 24% is in fact required. In practice, this means that to obtain a total kinetic energy extraction of 20% from the channel, 24% of the kinetic energy flux must be extracted for channel velocities of between 0.7 m/s (assumed cut-in speed) and 3.5 m/s (assumed rated velocity). The result is that at velocities approaching \( V_{\text{msp}} \) only 10% kinetic energy extraction will actually take place in this scenario, but it should be noted that these high velocities only occur for a limited amount of time (~10%) over a tidal cycle. It should also be noted that no energy extraction, and hence almost no effect, will occur at velocities below cut-in, and that these occur for ~20% of a tidal cycle. A total kinetic energy extraction of 20% requires mid-range kinetic energy extraction rates of 25% for the Channel Islands, and Mull of Galloway, and 28% for Rathlin Island.
Although the understanding of the SIF is in the developmental stage, it is clear that whilst the environmental effects of energy extraction that determine the SIF will be site specific, major issues to consider will be changes to:

- **Regional tide propagation** – Is considered unlikely to be affected by energy extraction at the Pentland Firth or Channel Island sites, but could be affected even by low levels of extraction at sites such as Rathlin Island or Islay.

- **Pollution transport/dilution** – The effects of energy extraction on pollution are not at this stage thought to be of primary importance in the most important sites, and it is noted above that the very high site velocities and very low velocities are less affected.

- **Sedimentation and other coastal processes** – Will be highly site specific, but for very high speed sites, such as the Pentland Firth, the channel will tend to be rocky with very little sedimentation. It is currently anticipated that small changes in velocity will have little effect since the maximum and minimum velocities are less affected.

- **Marine life** – Effects on marine life will also be highly site specific, and it is noted that various species of crustacean prefer relatively high flow velocities. However, since the maximum and minimum velocities are less affected than the mid-range velocities, it is thought that small changes in velocity will have less effect than might be expected.

In order to take a view of the total UK resource on the basis of currently available information, it is necessary to estimate SIF factors now, with only cursory consideration of possible environmental impacts. However, it is noted that this is no substitute for a proper study of environmental effects, in parallel with other stakeholder concerns.

### 4.3.5.3 Acceptable Mid-range Velocity Changes

Since low-range velocities and high-range velocities significantly less affected by tidal stream devices than mid-range velocities, the SIF is likely to be primarily dependent on acceptable changes to the mid-range velocity.

In the past, RGU have suggested that a 6% change in flow velocity represents a ‘safe’ change to velocities; this is based on the fact that changes to velocities of less than 6% are effectively un-measurable with present technology.

B&V believe that the environmental benefits of tidal stream energy should be considered in conjunction with any potential detrimental effects. Given the specific nature of the Pentland Firth sites, and the fact that the higher and lower flow velocities are less affected than the mid-range velocity, B&V believe that the mid-range velocity change that could be acceptable is likely to lie in the range 10-20%. Therefore at this stage, B&V have assumed that changes in mid-range velocity of 15% are deemed acceptable for the Pentland Firth.

Due to the more sensitive (environmental, tourist, and existing barrage at La Rance) nature of the Channel Islands, it has been assumed that only a 10% change in mid-range velocity is acceptable for these sites. For the Rathlin Island, Mull of Galloway and Islay sites, where there may be strong influences from energy extraction on the regional tide propagation, the 10% limit for the change in mid-range velocity is deemed acceptable.

It is possible that changes in mid-range velocity as high as 30% could be tolerated at certain sites.
4.3.5.4 Results of the RGU investigation

The key points from this latest work on the effects of different energy extraction regimes on tidal stream velocities for a (theoretical) Pentland Firth type site are discussed below:

Case 1 shows the effects for a channel representing the Pentland Firth of length 20km, width 14km, and 65m depth, with a depth-averaged velocity of 3.5 m/s. This case is intended to represent the effects at a flow velocity close to the tidal steam device’s rated velocity. Figure 4.2 shows the variation of surface elevation for varying extraction levels, whilst Figure 4.3 shows the variation of the depth-averaged velocity.

It is clear that as energy extraction increases, a larger proportion of the channel’s fixed (total) head drop occurs at the energy extraction position rather than over the length of the channel; the result of this is that the channel velocities are decreased. It is also clear that the incremental effects of an additional 5% extraction become greater at higher extraction, and the absolute extraction limit is reached at around 40% of the raw kinetic energy flux. The absolute limit will be
reached before the entire head drop, required to create the raw flow conditions in a channel with no extraction, occurs at the extraction point.

Case 2 shows the effects for the same channel, but with a depth-averaged velocity of 2.0 m/s. This case is intended to represent the effects at a flow velocity well below the device’s rated velocity (i.e., where devices are operating below rated power). Figure 4.4 shows the variation of surface elevation for varying extraction levels, whilst Figure 4.5 shows the variation of the depth-averaged velocity.

Figure 4.4 – Variation of elevation across the channel for varying extraction (case 2)

Figure 4.5 – Variation of velocity across the channel for varying extraction (case 2)

The results are clearly similar to those obtained for Case 1.
Case 5 shows the effects for the same channel, but with a depth-averaged velocity of 1.0 m/s. This case is intended to represent the effects at a flow velocity just above the tidal stream device cut-in velocity. Figure 4.6 shows the variation of surface elevation for varying extraction levels, whilst Figure 4.7 shows the variation of the depth-averaged velocity.

The results are clearly similar to those obtained for Cases 1 and 2, although the limit on kinetic energy extraction is lower. It should be noted that if there is a requirement for lower kinetic energy extraction percentages at lower velocities at a site (as might be implied by Case 5) then this will have a limited effect on the total resource at the site as there is little kinetic energy contained within the very low velocity streams.
In order to understand how the effects might vary with site depth, similar results were derived for a 90m depth. The results are similar, but since the head required for a deeper site is less (and inversely related to depth) the limit to the kinetic energy extraction percentage is also less (at ~ 20%) for the chosen parameters.

This can be clearly seen in Figure 4.8 below.

Figure 4.8 – Variation of elevation across the channel for varying extraction (case 3)

The variation in velocity with kinetic energy extraction for the different sites and velocities is shown in Figure 4.9.

Figure 4.9 – Variation of velocity for varying kinetic energy extractions and raw velocities

It is clear that for the 65m deep site (representing the Pentland Firth) the raw velocity is not particularly important, whilst for the 90m deep site (nominally representing the Channel Islands at lower kinetic energy extraction rates) the raw velocity is important, especially for velocity changes of over 10%.
4.3.5.5 Summary of the SIF Parameters

The key conclusions for the different sites can be deduced from the arguments in the above sections, and these are outlined in Table 4-4 below.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Mid-range Velocity Change (%)</th>
<th>Acceptable SIF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentland Skerries</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Stroma, P. Firth</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Duncansby Head, P. Firth</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Casquets, Channel Islands</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>S. Ronaldsay, P. Firth</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Hoy, P. Firth</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Race of Alderney, Ch. Is.</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>S. Ronaldsay, P. Skerries</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Rathlin Island</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Mull of Galloway</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 4-4 – Phase I Sites and SIF Parameters

It is important to note that, whilst these represent the best estimate based on current knowledge, future developments in the understanding of the factors affecting the SIF could change these key conclusions.

It has been pointed out that sites in the Channel Islands may behave similarly to sea lochs at high extraction rates, and therefore with full site exploitation the SIF that could be achieved for 10% change in velocity may be substantially greater than stated. On the other hand, the effects on the tidal barrage installation at La Rance need to be carefully quantified. Further detailed research work into the optimal development scenario for the Channel Island sites is required in order to validate whether higher SIFs could be achievable in practice.

Future research work for the key sites in the Pentland Firth should concentrate on the likely effects of energy extraction on the marine environment, and on further modelling that would account for both the variation in site width (and possibly depth), and the time varying nature of the tidal flows.
4.4 Phase II Results for Key UK Sites

4.4.1 Results for the key sites with a 20% SIF

The results with a nominal 20% SIF are detailed initially so that a direct comparison with the Phase I results can be drawn. The sites that are thought to have been double-counted at Phase I are eliminated, and the other sites are based on the updated parameters (other than the SIF) discussed in previous sections. Table 4-5 summarises the Phase II results for the key sites and draws the comparison to the results in Phase I.

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Site Name</th>
<th>Phase I (GWh/y)</th>
<th>Phase II (GWh/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pentland Skerries</td>
<td>3901</td>
<td>4526</td>
</tr>
<tr>
<td>2</td>
<td>Stroma P. Firth</td>
<td>2774</td>
<td>2114 (eliminated)</td>
</tr>
<tr>
<td>3</td>
<td>Duncansby Head</td>
<td>2031</td>
<td>1699</td>
</tr>
<tr>
<td>4</td>
<td>Casquets</td>
<td>1651</td>
<td>1045</td>
</tr>
<tr>
<td>5</td>
<td>S. Ronaldsay P. Firth</td>
<td>1518</td>
<td>1030</td>
</tr>
<tr>
<td>6</td>
<td>Hoy, Pentland Firth</td>
<td>1377</td>
<td>714</td>
</tr>
<tr>
<td>7</td>
<td>Race of Alderney</td>
<td>1365</td>
<td>608</td>
</tr>
<tr>
<td>8</td>
<td>S. Ronaldsay/ P.Skerries</td>
<td>1147</td>
<td>964 (eliminated)</td>
</tr>
<tr>
<td>9</td>
<td>Rathlin Island</td>
<td>866</td>
<td>1019</td>
</tr>
<tr>
<td>10</td>
<td>Mull of Galloway</td>
<td>806</td>
<td>638</td>
</tr>
<tr>
<td></td>
<td>Total top 10 sites</td>
<td>17,436</td>
<td>11,280</td>
</tr>
<tr>
<td></td>
<td>Total UK sites</td>
<td>21,812</td>
<td>15,655</td>
</tr>
</tbody>
</table>

Table 4-5 – Summary of Phase I and Phase II Available Resource for key sites (20% SIF)

The results show that the available resource at the most important sites has decreased from 17.4 TWh/y to 11.3 TWh/y. Approximately half of this reduction is due to the elimination of the two Pentland Firth sites and half due to changes in the input parameters. If the other UK sites are assumed to remain as in Phase I then the UK available resource is reduced from 21.8 TWh/y to 15.7 TWh/y. However it is likely that the other sites will experience a reduction due to changes in input parameters that is of the same order as for the most important sites, and therefore the UK resource could be expected to be reduced to approximately 15 TWh/y. This represents a reduction of 30% from the Phase I results.

As discussed above, it was decided that the initial Phase II result for the Pentland Firth (based on the summation of the original sites but excluding those sites thought to have their flux double-counted) should be compared with an estimate derived purely from a flux methodology taken across the eastern or western boundaries of the Pentland Firth, as also recently undertaken by the RGU in work for the Scottish Executive.

The B&V estimate of the Pentland Firth total resource, using this methodology with a SIF of 20% and updated site parameters, and calculated at the eastern boundary (expanding the original Phase I sites to cover the entire boundary), is 8.9 TWh/y. This can be compared to the result of 8.8 TWh/y obtained for the Phase I Pentland Firth sites (excluding flux double counting) in Section 4.3.2, and the result from the updated analysis (accounting for site parameter changes) of 8.0 TWh/y. These estimates may also be compared to some initial RGU results (for the Scottish Executive study) that we understand give 7 TWh/y, at the eastern boundary, and to results derived from the MEA that indicate a value of around 7 TWh/y.

Given the good correlation between the updated result for the individual sites obtained above of 8.0 TWh/y, and the three overall flux methodology results of 8.9 TWh/y and 7 TWh/y, it is logical to continue with the individual site results with the Stroma and S. Ronaldsay/Pentland Skerries results excluded.

The RGU result for the total Channel Islands resource (assuming a 20% SIF) is 2.0 TWh/y for all the Phase I sites, and this can be directly compared to the updated summation of the Channel Island sites which gives 3.0 TWh/y. RGU have also noted that some sites may be interdependent and this may reduce the resource; on the other hand they have also identified some new potential sites, and it was noted in 4.3.5.5 that practical SIFs may be higher. The RGU report for the Channel Islands can be found in Appendix 3, and a video file of the flow regime is available as Appendix 4.
4.4.2 Results for the key sites with updated SIFs

The results for the key sites with updated SIFs, as discussed above, are shown in Table 4-6:

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Site Name</th>
<th>Phase I (GWh/y)</th>
<th>Phase II (GWh/y)</th>
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<td>4526</td>
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<td>2</td>
<td>Stroma P. Firth</td>
<td>2774</td>
<td>2114 (eliminated)</td>
</tr>
<tr>
<td>3</td>
<td>Duncansby Head</td>
<td>2031</td>
<td>1699</td>
</tr>
<tr>
<td>4</td>
<td>Casquets</td>
<td>1651</td>
<td>418</td>
</tr>
<tr>
<td>5</td>
<td>S. Ronaldsay P. Firth</td>
<td>1518</td>
<td>1030</td>
</tr>
<tr>
<td>6</td>
<td>Hoy, Pentland Firth</td>
<td>1377</td>
<td>714</td>
</tr>
<tr>
<td>7</td>
<td>Race of Alderney</td>
<td>1365</td>
<td>365</td>
</tr>
<tr>
<td>8</td>
<td>S. Ronaldsay/ P.Skerries</td>
<td>1147</td>
<td>964 (eliminated)</td>
</tr>
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<td>9</td>
<td>Rathlin Island</td>
<td>866</td>
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<td>Mull of Galloway</td>
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<td>383</td>
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<td>Total UK sites</td>
<td></td>
<td>21,812</td>
<td>13,814</td>
</tr>
</tbody>
</table>

Table 4-6 – Summary of Phase I and Phase II Available Results for key sites (updated SIF)

These results show that the available resource at the most important sites has decreased by 35% from 17.4 TWh/y in Phase I to 11.3 TWh/y in Phase II after accounting for double-counted sites and input parameter changes, and by a further 17% to 9.5 TWh/y after accounting for changes to the assumed SIF. The net effect is a reduction of the resource at the most important sites by 45%.

If the other UK sites are assumed to remain as in Phase I then the UK available resource is reduced from 21.8 TWh/y to 13.8 TWh/y. However it is likely that the other sites will experience a reduction due to changes in input parameters that is of the same order as for the most important sites, and therefore the UK resource could be expected to be reduced to approximately 13.1 TWh/y. The other UK sites identified in Phase I are, in general, shallow water sites of around 30–40m depth, and represent varying types of site with respect to the SIF. Significant work would be required to estimate an updated SIF for these sites, and therefore it has been assumed at this stage that the average SIF for these sites remains at 20%. It should be noted that if SIFs of 12% were applied to the other Channel Island sites, and the potentially interdependent sites eliminated then the UK resource would be reduced by a further 0.9 TWh/y. If a lower SIF of 15% was applied to all the other UK sites then the UK resource would be reduced by a further 0.7 TWh/y. This demonstrates that the total UK resource is relatively insensitive to such changes, and that the UK resource estimate before the addition of any new sites is likely to be at least 11.5 TWh/y.

The Phase II resource estimate before the addition of any new sites is therefore 13.1 TWh/y. This represents a reduction of 40% from the Phase I result of 21.8 TWh/y.
4.5 Sites identified in Phase II

Phase I considered only sites that had been identified in previous literature, and did not set out to locate new sites. It was noted in some of the peer-review comments on the Phase I report that there are sites that were not included in Phase I, and therefore Phase II performed a review of potentially important new sites. This review was performed using the MEA as this is thought by the industry to contain the most up-to-date data on potential new sites. Rather than assess all the new potential sites from the MEA, this study concentrates on those sites that are expected to have the largest resource and be the most (economically) suitable for energy extraction.

Data was extracted from the MEA for each of the velocity and depth ranges shown in Table 4-1 and the results were compared with the locations that had been considered within Phase I. Possible extensions to the existing Phase I sites were not considered in this analysis since the MEA output cannot be readily configured to allow direct comparison with specific pre-defined areas (due to the relatively large 1.8km grid size and the fact that it cannot easily identify cells that are in fact on the same energy flux line).

The initial results of the analysis are shown in the maps overleaf.

Figure 4.10 shows the initial sites identified by the MEA where $V_{mp} > 1.5$ m/s, ranked by depth.

Figure 4.11 shows the initial sites identified by the MEA where $V_{mp} > 1.5$ m/s, ranked by $V_{mp}$.

It should be remembered that as the power in a tidal stream is related to the cube of the velocity, the power is likely to be concentrated in the areas with the highest velocities. This latter figure also shows the potential new sites (as purple stars) that are in areas that were not considered by the Phase I report.
Figure 4.10 – Sites from MEA with Vmsp >1.5 m/s ranked by depth
Figure 4.11 – Sites from MEA with Vmsp >1.5 m/s ranked by speed
Although there are many potential new sites identified by the outputs from the MEA, in comparison to the sites identified in Phase I many of these new potential sites are very small sites with low velocities ($V_{\text{mp}} < 2.5 \text{ m/s}$) and hence low energy resource. Many of these are also a significant distance from potential users / grid connections.

Despite this, there are a number of potential new sites that are of a reasonable size:

- The open-sea channel between SW Scotland and N. Ireland
- The open-sea channel between SW Scotland and the Isle of Man
- The open-sea area around NW Wales (Anglesey)
- The open-sea area around East Anglia
- The open-sea area of the English Channel between Dover and Calais
- The open-sea area within the English Channel along the S. coast of the UK
- Various estuarine channels

However, almost all of these have relatively low velocities ($V_{\text{mp}} < 2.5 \text{ m/s}$) and relatively shallow depths (<30m), and they are therefore expected to contain relatively little energy compared to the original Phase I sites.

The main areas that have higher velocities ($V_{\text{mp}} > 2.5 \text{ m/s}$), and which are therefore expected to contain a reasonable energy resource and be more (economically) suitable for energy extraction, are identified on the map as Islay, Carmel Head, and Isle of Wight. There are also some additional areas in the Channel Islands but these have been quantified separately through the additional RGU work on the Channel Islands resource.

The flux lines associated with these new sites are shown in Figure 4.12 below:

![Figure 4.12 – The new Islay, Carmel Head, and Isle of Wight sites from MEA](image-url)

It should be noted that the Islay site does not extend to landfall due to the shallow depths in the area. The energy resource associated with the flux lines shown above has been analysed using both the MEA and tidal stream atlases, and the results are shown in Table 4-7 below. The analysis assumes a 20% SIF as for the earlier UK sites.
Table 4-7 – Parameters for the new Islay, Carmel Head, and Isle of Wight sites

In Section 4.3.4.3 it was discussed that the MEA results for the tidal velocities are often different from those obtained from the tidal stream atlases, and this is very evident in the new sites. It is not always clear which is correct, but after analysis of the possible reasons for the differences, the following assumptions have been made:

- Carmel Head figures are based on the MEA data as the tidal stream atlas shows velocities at positions further from the coast than the main flux line chosen
- Islay resource figures are based on the average of the resource generated from the MEA and tidal stream atlas data
- Isle of Wight resource figures are based on the average of the resource generated from the MEA and tidal stream atlas data

Therefore, under these assumptions, the new sites have a total additional resource of 2.5 TWh/y.
4.6 Revised UK Resource Estimate

The updated UK resource for all the original sites, and including the three new sites, is therefore ~ 16 TWh/y, which is a reduction of 30% from the Phase I report figure of 22 TWh/y. The breakdown of this resource across the different types of sites is shown in percentage terms in Table 4-8 below. The figures in brackets are the equivalent figures quoted in the original Phase I report.

<table>
<thead>
<tr>
<th>Depth Range (m)</th>
<th>B&amp;V 2005 % Available Annual Energy Breakdown</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%) of 2004 Available Energy in brackets</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;2.5</td>
<td>2.5 – 3.5</td>
</tr>
<tr>
<td>&lt;25</td>
<td>0.2</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>(0.1)</td>
<td>(2.6)</td>
</tr>
<tr>
<td>25 – 30</td>
<td>0.1</td>
<td>2.3</td>
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<tr>
<td></td>
<td>(0.1)</td>
<td>(1.7)</td>
</tr>
<tr>
<td>30 – 40</td>
<td>8.8</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>(0.8)</td>
<td>(5.9)</td>
</tr>
<tr>
<td>&gt;40</td>
<td>11.1</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>(2.6)</td>
<td>(17.7)</td>
</tr>
<tr>
<td>Total</td>
<td>20.1</td>
<td>26.6</td>
</tr>
<tr>
<td></td>
<td>(3.5)</td>
<td>(27.9)</td>
</tr>
</tbody>
</table>

Table 4-8 – B&V 2005 / 2004 Available Annual Energy Breakdown

The significant changes and the reasons for these changes are outlined below:

In the 30–40m depth range:

- The % of energy within the 3.5–4.5 m/s range has been significantly reduced; this is due to the reduction in the tidal velocities from those in Phase I in the Race of Alderney (see Section 4.3.4.3).
- The % of energy within the 2.5–3.5 m/s range has been significantly increased; this is partly due to the reduction in the tidal velocities at the Race of Alderney, and partly due to the inclusion of the new site at the Isle of Wight where the significant discrepancy between the MEA and tidal atlas data (see Table 4-7) should be noted.
- The % of energy within the <2.5 m/s range has been significantly increased; this is wholly due to the inclusion of the new sites at the Carmel Head and Islay sites, and the significant discrepancy between the MEA and tidal atlas data (see Table 4-7) should be noted.

In the >40m depth range:

- The % of energy within the <2.5 m/s range has been significantly increased; this is wholly due to small changes in the tidal velocities at Casquets, Rathlin Island and Mull of Galloway.
- The % of energy within the 2.5–3.5 m/s range has been significantly decreased; this is wholly due to the small changes in the tidal velocities at Casquets, Rathlin Island and Mull of Galloway that has shifted their resource into the <2.5 m/s range.
• The % of energy within the 4.5–5.5 m/s range has been significantly decreased and that within the >5.5 m/s range has increased; these changes are wholly due to the exclusion in Phase II of the Stroma and South Ronaldsay/Pentland Skerries sites (see Section 4.3.2 and 4.4.1) and the consequent increase in the % of the UK resource that the Pentland Skerries site represents.

Overall, it is noted that deep sites (>40m) in Phase II represent some 63% of the UK resource (reduced from 79% at Phase I), and sites of depth 30–40m represent 30% of the UK resource (increased from 16% at Phase I).

It is important to note that the 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 > 40m.

It is clear that there is additional resource both around the new sites and within the other sites identified by the MEA, but this resource will be less easily exploited due to the lower power flux.

B&V believe that if all the additional sites identified in Figure 4.11 were analysed in a similar manner to the three new sites chosen and analysed above, the additional energy resource from these sites would be similar to that of the chosen new sites, and therefore the total UK available resource is expected to be around 18 TWh/y.

It is clear that there is considerable uncertainty in the estimate. This uncertainty is a result of two main factors:

• Uncertainty in the total energy resource, which is primarily dependent on accurate velocity data; the discrepancies between the MEA and the tidal stream atlases indicates that only detailed site measurements will clarify these velocities and allow more accurate resource figures to be obtained

• Uncertainty in the application of the SIF; clarifying the SIF for each site will require further detailed modelling of both potential environmental effects and different types of sites.

This uncertainty is calculated to be approximately +-30% for the total resource, although higher for the individual sites.
5 CONCLUSIONS AND RECOMMENDATIONS

The Phase I Report clearly showed that the use of only a Farm Method is no longer appropriate to determine the tidal stream resource. 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. The result is that the Farm Method needs to be constrained by a Flux Method that takes this resource availability into account. Based on initial work by RGU, the Phase I B&V 2004 model applied a 20% SIF to the total resource to develop an initial (single number) estimate for the Technically Extractable UK resource for comparison with previous figures. It was stressed that the chosen figure for the SIF was indicative and should be determined for each site individually. The UK Total Resource was estimated at ~110 TWh/y; the resulting UK resource for comparison with previous figures. It was stressed that the chosen figure for the SIF was indicative and should be determined for each site individually. The UK Total Resource was estimated at ~110 TWh/y; the resulting UK resource represents around half of the European Technically Extractable Resource. It was noted that much of this UK resource is concentrated in the Pentland Firth and the Channel Islands, and most of this UK resource is also to be found at depths greater than 40 m. It was also stressed that this initial estimate for the Technically Extractable Resource was expected to provide the upper limit and might well require (downwards) revision. It was recommended that further work be performed on a selection of prominent sites to establish more fully the appropriate SIF values. Since this Phase I study used previous data sources as a primary input, B&V noted that not all presently known sites were identified and quantified within this study. However, since a large proportion of the resource is located within a few well known locations it was considered unlikely that any highly significant sites had not been identified by this study, and therefore that the overall effect on the UK resource of any missing sites was expected to be relatively low.

This Phase II Report therefore concentrated on validating the input data (site widths, depths, and velocities) for the ten most important sites, by comparison of the data used in Phase I with data from the Marine Energy Atlas and Admiralty Chart / Tidal Stream Atlas data. Further work on the SIF was performed by both Black & Veatch and RGU in order to develop more detailed SIF estimates for the key sites.

The Phase II Report has concluded that:

- Two sites identified at the Pentland Firth by previous studies (and used in the Phase I study) cannot be included in the estimate of the UK resource using the flux methodology as a substantial portion of their energy flux is not independent from other sites. This conclusion has been validated by treating the whole of the Pentland Firth as one site using both Admiralty Chart / Tidal Stream Atlas and Marine Energy Atlas data. This change reduces the UK resource by approximately 15%.

- Updating the site parameters resulted in some relatively minor changes to width and depth of sites, but some significant changes to some site velocities. Whilst many of the velocities within the Tidal Stream Atlases and the Marine Energy Atlas are in agreement, there are some cases where there are substantial differences. The results from the Tidal Stream Atlases have in general been used in the analysis as they are generally of higher resolution. Four of the key 10 sites have reduced velocities that result in reductions in energy flux of more than 10%. The most affected site is the Race of Alderney where the original velocities used in Phase I appear to be just outside the UK’s territorial waters, and the energy flux at this site is reduced by 75%.

- Although the understanding of the SIF is in the developmental stage, it is clear that whilst the environmental effects of energy extraction that determine the SIF will be site specific, major issues to consider will be changes to: regional tide propagation, pollution transport / dilution, sedimentation and other coastal processes, and marine life. After analysis at this stage, B&V have assumed that changes in mid-range velocity of 15% are deemed acceptable for the Pentland Firth. Due to the more sensitive (environmental and tourist) nature of the Channel Islands, it has been assumed that only a 10% change in mid-range velocity is acceptable for these sites. For the Rathlin Island, Mull of Galloway and Islay sites, where there may be strong influences from energy extraction on the regional tide propagation, the 10% limit for the change in mid-range velocity is considered reasonable. SIFs for the key sites have then been estimated based on new modelling work by RGU for a theoretical Pentland Firth site.

- The Marine Energy Atlas identifies many potential new sites, but many of these are small sites with low velocities. There are a number of potential new sites of reasonable size, but again many have low velocities. The main areas that are of both reasonable size and reasonable velocity (>2.5 m/s) are located at Islay, Carmel Head, and the Isle of Wight.
The updated Phase II Technically Extractable UK Resource is 18 TWh/y, a reduction of 20% of 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 Island, Rathlin Island, and Mull of Galloway sites.

Approximately 20% of this UK resource is within sites of depth 30–40m that have $V_{nsp}$ between 2.5–4.5 m/s. These are probably the sites most (economically) suited to near term developments that use seabed-standing devices (using for example monopile designs). Approximately 50% of the UK resource is within deep (>40m) sites that have $V_{nsp}$ >3.5 m/s; these are only suited to device designs that are capable of being installed and operated in water depths > 40m.

It is clear that there is uncertainty in the estimate which is a result of two main factors:

- Uncertainty in the total energy resource, which is primarily dependent on accurate velocity data; and the discrepancies between the MEA and the tidal stream atlases indicates that only detailed site measurements will clarify these velocities and allow more accurate resource figures to be obtained.
- Uncertainty in the application of the SIF; clarifying the SIF for each site will require further detailed modelling of both potential environmental effects and different types of sites.

This uncertainty is calculated to be approximately +-30% for the total resource, although higher for the individual sites. This clarification of the resource through detailed measurement and modelling will be important for site developers, and given the scale of the resource outlined above it is recommended that this be supported.

In conclusion, this Phase II report has reduced the estimate of the total UK resource to ~18TWh/y, a reduction of 20% from the Phase I result. Nevertheless, the UK has a significant tidal stream Technically Extractable Resource (around 5% of UK electricity demand), and this resource probably represents around half of the European Technically Extractable Resource and between 10-15% of the known global Technically Extractable Resource as outlined in Phase I.
GUIDE TO APPENDICES

Appendix 1 – Contribution to BV2004 Resource by Site

Appendix 2 – Comparison of BV2004 / 2005 Input Parameters

Appendix 3 – RGU Study – Channel Island Resource

Appendix 4 – RGU Tidal flow visualisation for the Channel Islands (.AVI video file)
Appendix 1 – Contribution to BV2004 Resource by Site
<table>
<thead>
<tr>
<th>Rank</th>
<th>Phase 2 Rank</th>
<th>Phase 1 No.</th>
<th>Site Name</th>
<th>Grid Ref.</th>
<th>Width (m)</th>
<th>Depth (m)</th>
<th>Vsp (m/s)</th>
<th>Vnp (m/s)</th>
<th>Vsp/Vnp Ratio 1st/2nd Tide</th>
<th>Rated V (m/s)</th>
<th>BV2004 Extractable &amp; Available Annual Energy (GWh/site)</th>
<th>Cumulative Annual Energy (GWh/site)</th>
<th>Cumulative contribution to UK resource (%)</th>
<th>Individual Contribution to UK resource (%)</th>
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</thead>
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<td>2.34</td>
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<td>3.66</td>
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<td>3</td>
<td>6</td>
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<td>71</td>
<td>5.15</td>
<td>2.20</td>
<td>2.34</td>
<td>0.88</td>
<td>3.66</td>
<td>2774</td>
<td>17.8%</td>
<td>17.8%</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>17</td>
<td>Carrow</td>
<td>56°47N, 2°25W</td>
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<td>118</td>
<td>2.07</td>
<td>1.19</td>
<td>1.85</td>
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<td>7.6%</td>
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<td>5</td>
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<td>3.11</td>
<td>1517</td>
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...
Appendix 2 – Comparison of BV2004 / 2005 Input Parameters
## Appendix 2 - Comparison of 2004 / 2005 Input Parameters

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<th>Site Name</th>
<th>2004 Width</th>
<th>2005 Width</th>
<th>Width MEA Model</th>
<th>Width Calc MEA</th>
<th>2004 Vsp Depth MEA</th>
<th>2005 Vsp Depth MEA</th>
<th>2004 Vnp Depth MEA</th>
<th>2005 Vnp Depth MEA</th>
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</thead>
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<td>76</td>
<td>72</td>
<td>56.0</td>
<td>68.0</td>
<td>4.38</td>
<td>3.70</td>
<td>3.60</td>
</tr>
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<td>S. Ronaldsay P. Firth</td>
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<td>63</td>
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<td>Duncansby Head</td>
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<td>2.26</td>
<td>2.25</td>
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### Notes
- **Width**: For race of Alderney width increased as wider part of the site area falls closer to the Tidal stream data point.
- **Depth**: Differences in depth due to averaged depth values of whole site area taken from Ad. Charts. BV 2005 values show good likeness to MEA calculated depths.
- **Vsp and Vnp**: Alderney value lower because different tidal stream atlas values used (point closer to site area). Differences in MEA values because of large grid size used.
Appendix 3 – RGU Study – Channel Island Resource
Tidal Stream Resource Assessment for The Channel Islands area

For Black & Veatch Consulting Limited

By Alan Owen, The Robert Gordon University, Aberdeen

This report was prepared by The Robert Gordon University for Black & Veatch Consulting Limited for their sole use. It is based on an indicative model using information available in the public domain.

30/03/05
Introduction

Black & Veatch Consulting Limited (B&V) has recently reviewed estimates of tidal stream resources and the techniques used therein. One particular report that considered UK sites in detail has been examined closely. The 1993 ETSU report [3] was generated using the tidal stream ‘farm’ methodology, which assumes that a grid of devices is installed and that the extractable energy is a function of the installed capacity. Whilst this method is broadly applicable to wind farms, it is not suitable for tidal stream energy exploitation due to the fact that it is possible for the calculated energy output to exceed the energy available.

An alternative method is being developed by The Robert Gordon University in which, the total energy flux through a site is calculated based on existing empirical data available in the public domain. Having defined the total energy flux available, the Significant Impact Factor (SIF) parameterises the exploitable energy, which seeks to determine the maximum energy that may be extracted without causing significant changes to the flow regime. The SIF has been tentatively set at 20% as an average figure, and it is considered that the figure will be site specific and dependent on flow drivers, bathymetry and other physical conditions. This report looks at the resource within the Channel Islands area and contrasts the results from the new flux methodology, with the 1993 report based on the farm methodology.

Methodology

The accuracy and cost effectiveness of the method depends on the ready availability of data, which has already been validated and is generally accepted as being reasonably accurate. Pictorial data can be found from a variety of publications including bathymetry from British Geological Survey maps and tidal stream vectors from the Admiralty Tidal Stream Atlas.

For the Channel Islands study, bathymetry data was used from BGS Sheet 49N 04W (Guernsey) [1], Admiralty Chart 2669, and tidal stream data was taken from Admiralty Tidal Stream Atlas NP264 (Channel Islands) [2]

Bathymetry

The bathymetry image is stripped of all information not required by the programme, leaving only contour lines and landmasses identified. The bathymetry is defined using individual colours for each of the bathymetric contours and for the landmasses, leaving the spaces in between as unknowns. The programme then scans the picture and generates an array of numerical contour values from the colour found at each vertex, using a linear interpolation algorithm to produce values for the vertices where no colour is identified.

Tidal stream data

In a tidal stream atlas the vectors are usually scaled in groups according to the strength of the flow that they represent and the programme allows for this by providing a vector scaling capability. For the Channel Islands however, this is not the case, and each vector has to be individually specified. The effects of flow momentum between the head of one vector and the
tail of preceding vectors can also be modelled according to the strength of flow. The vector field (Fig.1) is input by overlaying the relevant tidal stream vector image over the bathymetric contour image and using the mouse click event to indicate the start and end points of each vector. These start and end points, along with variables indicating the strength of flow and momentum effects, are stored in a list box to be processed later in the programme. Outlines of landmasses are used to check the alignment of the vector map when overlaid onto the bathymetry graphic using the Visual Basic overlay command. Any land mass is given a zero vector value and boundary conditions for the graphics’ edge are found by using an average value of the nearest available vectors.

![Figure 1 Tidal stream vectors for Channel Isles](image)

The programme first identifies what information it has available to it by scanning the image, recognising any landmasses present, and imports the flow vectors from the listbox which holds the values defining the vector start and finish co-ordinates. The vector magnitude is then modified according to the user-defined variables describing the strength of flow and momentum effects. Before continuing, the known flow vectors and their associated momentum vectors, are drawn for approval and/or modification by the user. The programme then scans the picture, attaching known vector X and Y component values at each vertex, interpolating for any missing values and passing the results to an array, the coordinates of which coincides with the bathymetric coordinate system. The X and Y vector components are stored in separate arrays in order to reduce the number of string splitting and re-assembling operations. Once the interpolation process is complete, the vector components are smoothed by averaging over surrounding values to a maximum distance set by the user. Zero value vector components attached to landmasses are reasserted at this point to prevent the algorithmic erosion of the coastlines.

The vectors are assembled and their magnitude and direction (in degrees) are written to a final array for visual interpretation, printing to file etc. The image is then redrawn using the vector magnitude to govern the colour used in the image i.e. white (RGB(255,255,255))
indicates <0.05m/s flow and black(RGB(0,0,0)) indicates a flow speed in excess of 6m/s. (see fig.2 overleaf)

Combining Bathymetry and Flow Vectors
At this point, there exists a number of arrays holding information on flow speed and flow direction for each 1 hour period of the flow/ebb cycle as well as the bathymetry and land masses, all of which use the same X, Y co-ordinate system. Therefore at any given vertex (or vertices) linked information can be utilised. For example, if the surface velocity is known, and assuming that the surface flow is indicative of the flow profile, a reasonably representative flow profile can be obtained using the 1/7th power law. Applying the power law to describe the flow profile with respect to depth, the programme creates a quasi-3D velocity matrix, which can be queried for a variety of data. For example, the data can provide information on the energy flux through any chosen cross section on the image or calculate the CSA of the flow at any point.
Time series interpolation

In this study, the data files for each one-hour interval are read into the program and assembled into a three-dimensional array. By extracting the data at any chosen section, a 13-point, approximately 1-hour interval, time series is found for the tidal stream velocities at that section, (in actual fact the flow/ebb cycle is generally taken as being 12.5 hours). Application of a second order Lagrange interpolating polynomial generates intermediate values at quarter hour intervals. Similarly, for the 14-day Spring/Neap cycle, tide tables provide twice daily high water and low water values for a nearby port that can be used to model the cyclical variation of the tidal stream velocities at the point. Taking the difference between the HW and LW heights and normalising for the Spring peak, gives a factor which, when applied to the Spring values used by the program, models the Spring/Neap cycle from Spring values only.

Between each vertex in the cross section, which on the scale used, represents a distance of 210m, the power is calculated as follows:-

The program has generated X and Y vector components at each vertex (X\text{vect}, Y\text{vect}), from which, the velocity vector (V_{vel}) may be defined.

\[ V_{vel} = \sqrt{(X_{\text{vect}}^2 + Y_{\text{vect}}^2)} \quad \text{eqn 1} \]

The length of the section can be found from the start and finish X,Y co-ordinates,

\[ L_{\text{section}} = \sqrt{(X_{\text{start}}^2 - X_{\text{end}}^2) + (Y_{\text{start}}^2 - Y_{\text{end}}^2)} \quad \text{eqn 2} \]

The CSA (A) is defined by the scale width (210), the length of the section in terms of the graphics X,Y co-ordinates and the section depth (D) at the vertex, ie

\[ A = 210 \times D \times L_{\text{section}} \quad \text{eqn 3} \]

To obtain hourly power (Whr) figures through the section from ¼ hour intervals, eqn 4 is used for each ¼ hour interval and the sum taken of four consecutive intervals.

\[ P = 0.5 \times \rho \times A \times V_{vel}^3 \quad \text{eqn 4} \]

The resulting hourly figures are summed for the 13 hr flood/ebb cycle giving a total power flux through the section in Whr per flood/ebb cycle.

\[ P_{\text{FE}} = \sum_{i=1}^{13} P \quad \text{eqn 5} \]
These power totals are then transferred to a spreadsheet where the equivalent velocity that would be required to generate that power in that period is calculated from the total power flux, ie

\[ V_{eq} = \sqrt[3]{\left( \frac{P}{\rho A} \right)/0.5} \quad \text{eqn 6} \]

The ratio of high water to low water for a nearby port eg St Helier, provides a reasonable model for the Spring/Neap cycle. Normalising the ratio to the Spring maximum gives a factor \((\gamma)\), which may be applied to the 14 day cycle. Using St Helier as a pattern, this factor can be calculated for each site from the Spring/Neap values in the Tidal Stream Atlas.

Data taken from Tide Table St Helier, Jersey, 49.1667N,2.1000W

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<th>Normalised((\gamma))</th>
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Table 1 HW/LW difference, normalised to spring peak
Ref: http://www.mobilegeographics.com:81/calendar/month/5470.html
Since the equivalent velocity $V_{eq}$ represents the velocity required to generate the calculated power through any given section at Spring peak over a period of 13 hrs, variation of this velocity in proportion to the difference between high water and low water (Combined Normalised ($\gamma$) in table 1 above), will permit a reasonable approximation of the velocity variation with the Spring/Neap cycle (eqn 7). The resulting total, ($P_{cycle}$) multiplied by 26 will give an annual power output, ($P_{annual}$), at the section, based on the Spring peak $V_{eq}$ for that section. (eqn 8).

$$P_{cycle} = \sum_{i=1}^{28} 0.5 \cdot \rho \cdot A \cdot (\gamma \cdot V_{eq})^3$$ \hspace{1cm} \text{eqn 7}$$

$$P_{annual} = P_{cycle} \cdot 26 \text{ (GWhr)}$$ \hspace{1cm} \text{eqn 8}$$

Whilst the method is clearly an approximation, it does accommodate the variations both within the flood/ebb cycle and the Spring/Neap cycle, based on 15 minute intervals.

**Define Area & sections**

For the purposes of this study, the general area to be examined is outlined by the lat/long coordinates, 48.500°N, 1.500°W to 50.000°N, 3.000°W (fig.3 overleaf). Six sites are identified, five of which were previously assessed in [3]. This methodology generates comparative data for these five sites.

The cross sections considered to be of interest for this study are illustrated in fig 3 overleaf and listed below:-

CSEC1: Guernsey (49.416°N, 2.633°W) to Pte de l’Arcouest (48.816°N, 3.000°W)

Broad cross section of medium speed flow.

CSEC2: Race of Alderney, (49.720°N, 2.14°W) to (49.705°N, 2.067°W), compared with Site 16 – Race of Alderney, [3]

CSEC3: Big Russel, Guernsey (49.460°N, 2.445°W) to (49.440°N, 2.390°W)

Compared with Site 19 – Big Russel

CSEC4: North East Jersey, (49.250°N, 2.060°W) to (49.273°N, 2.040°W)

Compared with Site 20 – North East Jersey

CSEC5: Casquets, Channel Islands, (49.748°N, 2.398°W) to (49.811°N, 2.472°W)

Compared with site 17 – Casquets

CSEC6: NW Guernsey (49.602°N, 2.791°W) to (49.517°N, 2.700°W)

Compared with Site 18 - North West Guernsey
The Lat/Long co-ordinates are converted to X,Y co-ordinates in relation to the graphic. Note that for ease of manipulation the X,Y coordinates are aligned with the Visual Basic system, which denotes the origin (0,0) as top left.

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<th>Long</th>
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*Figure 3*
Approximate illustrative locations of the various sections.
The site graphic as used by the program measures 461(W) x 724(H), producing data at 333764 vertices with depths varying from 0m to 80m, in increments of 1m.
CSEC1 was chosen for its approximate perpendicularity to the average flow for the majority of the tidal cycle and because initial visual inspection suggested a phase difference would be found between this and CSEC2. The remaining sections were taken for the purposes of comparison with the 1993 report. [3]

Results

Model Validation
The model is run for each image combination representing 13 x 1 hour (approx) intervals of the tidal cycle. The resulting greyscale image is then checked for correlation with the known values as given in the Tidal Stream Atlas. By clicking on the image, a text box shows the X,Y co-ordinates at the point and displays the vector speed and direction at that point. In previous work, (Pentland Firth and The Orkney Islands), the vectors are scaled to a reasonable level of accuracy. In the case of the Channel Islands, no scaling was inherent within the vector images and each image was tuned individually to a variation of +/- 5%. The section between Guernsey and Alderney was not included since, when viewed with the direction of flow, the CSA available for most of the tidal cycle is minimal. Also, in its present configuration, the methodology is not yet comparing flow direction with the relative direction of the chosen section, although this will be available in future versions. The methodology examines the flux at the boundary, regardless of direction, and assumes that any energy extraction method would be capable of aligning itself with the prevailing flow.

The AVI file below shows the flux represented in greyscale over the 13 hour period at 1 hour intervals.
Results
The output from the software is collated into tables (see appendix), which provides numerical values for the Channel Islands tidal resource. Figures shown in brackets refer to those available in the 1993 report.

CSEC1: Guernsey (49.416°N, 2.633°W) to Pte de l'Arcouest (48.816°N, 3.000°W)
The site covers a broad spread of variable speed flow between the north coast of France and the south coast of Guernsey, and is primarily driven by the head difference between the Baie du Mont Saint Michel and the English Channel.

Bathymetry
The maximum depth is found as 60m, which correlates well with Chart 2669. Average depth is 53m and the width of the section is 63210m

Velocities
Peak flow speed across this section is given as 2.09m/s at +4hrs(HW, Dover) by the program, which compares with 2.15m/s at +4hrs(HW, Dover) shown in the Tidal Stream Atlas. Peak spring/neap ratio is 2.26.

Resource
Total flux across the section is 8491 GWhr/yr. If a 20% SIF is assumed, this suggests an available resource of 1698 GWhr/yr. Annual power as a function of CSA is 2.75 MWhr/m²

CSEC2: Race of Alderney, (49.720°N, 2.14°W) to (49.705°N, 2.067°W), compared with Site 16 – Race of Alderney, [3]

Bathymetry
The maximum depth is found as 46m, which correlates reasonably well with Chart 2669 giving a spot depth of 42m. Average depth is 40.1m and the width of the section is 4936m

Velocities
Peak flow speed across this section is given as 4.5 m/s (4.4m/s) at -3hrs(HW, Dover) by the program, which compares with 4.4 m/s at -3hrs(HW, Dover) or 4.8 m/s at -4hrs (HW, Dover) shown in the Tidal Stream Atlas. Peak spring/neap ratio is 1.88 (1.82).

Resource
Total flux across the section is 3628 GWhr/yr. If a 20% SIF is assumed, this suggests an available resource of 726 Whr/yr (5187 GWhr/yr). Annual power as a function of CSA is 18.3 MWhr/m²
CSEC3: Big Russel, Guernsey (49.460°N, 2.445°W) to (49.440°N, 2.390°W)

Compared with Site 19 – Big Russel

**Bathymetry**
The maximum depth is found as 36.6m, which correlates well with Chart 2669 giving a maximum spot depth of 37m. Average depth is 24.5m and the width of the section is 4056m.

**Velocities**
Peak flow speed across this section is given as 2.6 m/s (2.8m/s) at -5hrs(HW, Dover) by the program, which compares with 2.6 m/s at -5hrs(HW, Dover) shown in the Tidal Stream Atlas.
Peak spring/neap ratio is 1.97 (n/a).

**Resource**
Total flux across the section is 822 GWhr/yr. If a 20% SIF is assumed, this suggests an available resource of 164 GWhr/yr (2000 GWhr/yr). Annual power as a function of CSA is 8.3 MWhr/m²

CSEC4: North East Jersey, (49.250°N, 2.060°W) to (49.273°N, 2.040°W)

Compared with Site 20 – North East Jersey

**Bathymetry**
The maximum depth is found as 20m, which correlates well with Chart 2669 giving a maximum spot depth of 23m. Average depth is 20m and the width of the section is 2599m.

**Velocities**
Peak flow speed across this section is given as 2.6 m/s (3.1m/s) at +4hrs(HW, Dover) by the program, which compares with 2.6 m/s at +4hrs(HW, Dover) shown in the Tidal Stream Atlas.
Peak spring/neap ratio is 1.8 (1.8)

**Resource**
Total flux across the section is 282 GWhr/yr. If a 20% SIF is assumed, this suggests an available resource of 56 GWhr/yr (1403 GWhr/yr). Annual power as a function of CSA is 5.43 MWhr/m²

CSEC5: Casquets, Channel Islands, (49.748°N, 2.398°W) to (49.811°N, 2.472°W)

Compared with site 17 – Casquets

**Bathymetry**
The maximum depth is found as 71.6m, which correlates reasonably well with Chart 2669 giving a maximum spot depth of 79m. Average depth is 70.1m and the width of the section is 7810m.

**Velocities**
Peak flow speed across this section is given as 2.4 m/s (2.6m/s) at -4hrs(HW, Dover) by the program, though there is no immediate figure shown in the Tidal Stream Atlas, the closest suggests 1.95m/s at –3hrs(HW, Dover). Likewise, peak spring/neap ratio is approximately 1.8 (1.85)
Resource
Total flux across the section is 2933 GWhr/yr. If a 20% SIF is assumed, this suggests an available resource of 587 GWhr/yr (2943 GWhr/yr). Annual power as a function of CSA is 5.36 MWhr/m²

CSEC6: NW Guernsey (49.602°N, 2.791°W) to (49.517°N, 2.700°W)
Compared with Site 18 - North West Guernsey

Bathymetry
The maximum depth is found as 70m, which correlates well with Chart 2669 giving a maximum spot depth of 65m. Average depth is 69.7m and the width of the section is 10199m.

Velocities
Peak flow speed across this section is given as 2.1 m/s (2.1m/s) at +2hrs(HW, Dover) by the program, which compares with 2.05 m/s at +2hrs(HW, Dover) shown in the Tidal Stream Atlas. Peak spring/neap ratio is 2.6. (1.85)

Resource
Total flux across the section is 2530 GWhr/yr. If a 20% SIF is assumed, this suggests an available resource of 506 GWhr/yr (4402 GWhr/yr). Annual power as a function of CSA is 3.56 MWhr/m²

Discussion
The program output generally achieves a high degree of correlation with the Tidal Stream Atlas, and the bathymetry and flow dimensions of the 1993 report. Whilst the 1993 report mentions installed capacity and resulting output, it is likely that the 1993 report assumed a much higher level of installed capacity than would be considered now.

It is apparent from the Tidal Stream Atlas that the Channel Islands area partially behaves in a manner analogous to a sea loch, in that the flow is forced towards the Baie du Mont Saint Michel where it is held by the tide rising in the English Channel. Some of the flow which passes through CSEC2 is from the periphery of the English Channel flow at +6,–6,–5, +1,+2,(hrs relative to HW @ Dover) whilst at –4,–3,–2,–1,HW,+3,+4,+5,+6, the site is filling and draining with a change in head, rather than running as a channelled flow. It is therefore very likely that the proposed SIF of approximately 20% may be different for the sites within this area. Extraction of energy from this area would impact on the performance of the barrage at La Rance, since energy extraction would change the head available at the barrage site.

The overall spring/neap ratio is not constant for the sites within the area, varying from 2.94 at HW Dover, to 1.76 at +5Hrs(HW, Dover). The Race of Alderney (CSEC2) provides the best power availability per m², with an annual average of 18.31 MWhr/m².
This study models the power available at each site when considered individually, but CSEC2 and CSEC3 are interdependent as are CSEC5 and CSEC6. Their interdependency varies through the flood/ebb cycle, i.e. for both pairs of sites, no interdependency exists at HW-2 and HW-1, when there is little flow present through either, but major interdependency exists at HW-5 and HW-4, when there are large flows through both.

Further modelling is required to establish the true power resource for the Channel Islands, but a reasonable approximation is of the order of 1.5 – 2.5 TWhr/yr, assuming an SIF of 20%. The model itself appears to obtain reasonably accurate flow velocities but requires a more flexible algorithm for interpolating the bathymetry.

**Conclusions**

The graphical flux method is relatively quick to produce results but relies entirely on the accuracy of the original data. However, the data employed is as measured by the Hydrographic Office rather than produced by theoretical equations as used in more sophisticated CFD packages. The correlation with the measured data on the vector graphics is generally of the order of +/- 5% and therefore is considered to be a reasonable reflection of the flow as mapped. It is not possible to take into account any shear flows at depth, and these would need to be determined by site measurements.

The Channel Islands area appears to offer a usable resource of 1.5 – 2.5 TWhr/yr based on the proposed SIF of 20%, but exploitation at one site will have an effect on neighbouring or downstream sites. Exploitation on any commercial scale will affect the HW/LW cycle at the existing tidal barrage site at La Rance. More accurate modelling of the effects of energy extraction on the head is required to quantify this effect. This study has excluded the area between Alderney and Guernsey, since the energy extracted at this point would largely be available at the other sites.

**References**

1. BGS Map, Guernsey Sheet 49N 04W, Scale 1:250000, NERC
3. ETSU Tidal Stream Energy Review, Report T/05/00155/REP, 1993
Appendix 4 – RGU Tidal flow visualisation for the Channel Islands

This is a video file (.avi) and has been delivered separately.