Carbon Trust Foreword to UK Tidal Current Resource and Economics Study.

This study has been commissioned by the Carbon Trust, with support from The Crown Estate and npower's Juice Fund, to improve our understanding of the potential for tidal stream energy generation in the UK[1]. The study runs in parallel with an equivalent assessment of UK wave resource, which uses the same approach of understanding the 'total', 'technical' and 'practical' resource. The technical resource is that which could theoretically be extracted within reasonable environmental and cost constraints, while the practical resource also takes into account practical spatial constraints. The results of this study are being used by the Carbon Trust to inform innovation support in the marine energy sector, and by the Crown Estate to inform strategic planning and future leasing of marine energy sites.

This tidal study uses a new hydrodynamic methodology developed by Edinburgh University's Institute for Energy Systems, and updates our previous work UK tidal stream resource published in 2005. This new study takes into account practical constraints to development on a UK wide basis as well as environmental and economic factors. It also provides for the first time, the likely cost of energy differences between each of the tidal sites considered. The hydrodynamic methodology developed for this study is an extension of the methodology that was first proposed in 2006 as a 'Flux method'. This report uses the same underlying principle – that extracting energy from a tidal stream impacts on the flow and therefore what is available elsewhere in the stream – but with a significantly improved understanding of hydrodynamic mechanisms (resonant basins, hydraulic currents and tidal streaming). The methodology and results have been reviewed by experts in the UK, US and New Zealand.

The 2011 *Tidal Current Resource and Economics* report suggest s a total of 20.6 TWh per year could practically be extracted from the 30 key tidal stream sites in the UK . This is our best estimate of the maximum amount of electricity that could be generated by currently foreseeable tidal devices technologies without a 'significant' impact on either the economics of energy extraction, or on the environment. Applying different acceptable impact levels, as discussed in the report, could increase the resource available by up to 40%. The practical constraints assessment also implies a balance between other sea uses (shipping, fishing and designated conservation areas are particularly relevant for tidal energy extraction); if the balance of priorities was to shift towards energy extraction then the total practical resource could increase from 20.6 TWh towards 29 TWh per year. The 2011 study increases the base case available energy (technical resource) by some 60% compared to the 2005 figure.

The study has been able to apply costs of energy extraction for each site identified because of the Carbon Trust's involvement with leading tidal energy technology developers, and these costs are aligned with the industry baseline costs published in July 2011 (*Accelerating Marine Energy).* The costs presented show that sites with higher velocities have the potential for significantly cheaper

[1] This study includes the British Channel Islands

cost of energy than the lower velocity sites. The Carbon Trust has also looked at the challenges associated with each site: while high velocity sites have the potential to be most economic, they do also tend to be the most difficult to design for, install and operate in. This leads to the important conclusion, which is discussed in depth in the Carbon Trust's 2011 report *Accelerating Marine Energy,* that innovation of leading technologies, and perhaps a new generation of technologies will be needed in order to exploit these difficult and deep sites.

This work is a significant advance on the 2005 Carbon Trust study in terms of accuracy and resolution of analysis. The results could be improved by better input data and by agreement from statutory environmental bodies on what environmental impacts are acceptable, but we believe this report provides the best estimate of the UK tidal resource to date. The potential for tidal stream energy in the UK remains significant, and we hope this report provides a useful resource to the industry to show the scale of potential market in the UK, and also to direct future innovation thinking.

(July 2011).

UK Tidal Current Resource & Economics

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EXECUTIVE SUMMARY

In 2004/5, as part of the Carbon Trust's Marine Energy Challenge (MEC), Black & Veatch (with input from University of Edinburgh) defined a 'Significant Impact Factor' (SIF) to estimate the UK's 'extractable tidal stream resource' (the equivalent parameter is called the 'technical tidal current resource' in this report), representing the percentage of the total tidal stream resource at a site that could be extracted without significant economic, environmental or ecological effects. Since the initial investigation, limited research has been reported on the SIF, although Black & Veatch and the University of Edinburgh have undertaken some specific site assessments. Due to various studies published since 2005, further work on understanding how to quantify the technical resource at individual sites, as was recommended in Black & Veatch's 2005 report, remained important, and was commissioned as part of the Marine Energy Accelerator, with support from the Juice fund and the Crown Estate. This work is the subject of this report.

Appendix C summarises the underlying hydrodynamic modelling work that informs this report. The focus of the work presented in Appendix C is the far-field response of the tidal system with regard to the economic and environmental implications of widespread, large-scale TEC (tidal [current] energy converter) deployment. The approach adopted is to consider ideal representations of each of the (three) relevant hydrodynamic mechanisms which give rise to the tidal current conditions necessary for TEC deployment. In all three tidal regimes, an upper *theoretical limit* was identified beyond which attempts to extract more energy from the system actually reduces the overall energy that is harvested. This indicates the existence of a theoretical extraction limit in a particular location using the TEC technology approach. This highlights that the outdated 'farm' resource assessment methodology[1] is fundamentally flawed, as first indicated in the 2004/5 MEC reports. The flow discharge, flow velocities and tidal range were all reduced by energy harvesting, as expected, and these effects would at some point have impacts on the environment and the project economics that would be unacceptable, as outlined in the 2004/5 MEC reports. Generic expressions have been derived to allow the parametric national scale resource study to be updated, and arbitrarily prescribed limits for mid-range velocity and tidal range changes were then applied to allow the derivation of an update to the UK's technical resource[2].

The latest 2008 version of the Marine Energy Atlas (MEA) was used as primary source of data for the 2011 UK tidal current resource assessment. All sites from the MEA with a mean annualised power density in excess of 1.5kW/m^2 and a depth in excess of 15m have been included in this analysis. The Carbon Trust and Black & Veatch acknowledge that technologies specifically designed for low power density sites (such as Minesto, which was supported during the Marine Energy Accelerator) could potentially result in lower power density sites becoming economic; however, these are not considered in the analysis as their performance is not well enough understood.

The underlying costs and scaling parameters used in the Black & Veatch 2011 model were derived from work undertaken by Black & Veatch in the Marine Energy Accelerator. The '1st generation

[1] Farm method – Energy extraction methodology used in most studies previous to the 2004/5 MEC study and based on an array of TECs that each extract an equal amount of energy from the incoming current. The number of devices and the extracted energy is purely dependent on the size of the device, its efficiency, and the packing density within the plan area.

[2] Technical resource – The energy that can be harvested from tidal currents using envisaged technology options and restrictions (including project economics) without undue impact on the underlying tidal hydrodynamic environment. The technical resource was referred to as the 'Extractable Resource' in the 2004/5 MEC reports.

technology' costs (without learning) are expected to be representative of first commercial farm costs, and are based on technology that is already largely proven. A '2nd generation technology', which is based on the 1st generation technology but represents a step-change economic improvement rather than incremental learning is assumed to become available and is used in the model from the Pentland Firth Deep site onwards. It should be noted that if such 2nd generation technologies are not developed successfully, then the cost-of-energy (CoE) for Pentland Firth Deep, and all later sites, could be expected to be substantially higher (c. 20%+). Grid connection costs only include initial high level estimates of the costs of connection to a shore based transformer/grid connection station. No upgrades of the distribution or transmission network, or system use charges are included, as these cannot be estimated on a generic basis. These costs could be significant for sites that are remote from the present grid network, or where the grid is weak, or ongoing transmission capacity is limited. Pentland Firth is a notable example of such a site.

Standard statistical analysis has been used to derive final error bands on total UK Annual Energy Production (AEP) and UK averaged CoE. The overall results are shown in the table below (CoE with discount rate (d.r.) 15%).

	Total Technical resource	**Average CoE with learning**
	TWh/y	p/kWh
Pessimistic (P10)	16.4	42.4
Base (P50)	29.0	19.7
Optimistic (P90)	38.4	14.8

It should be noted that the UK averaged CoE has been obtained after averaging all CoE weighted by their AEP. The most influential parameter on the pessimistic CoE figure is the actual resource data used to assess the sites, due to the significant uncertainty prescribed to the MEA data. The assumed CoE and tidal range limits are the most influential parameters on the AEP, each influencing the AEP estimate by c. +/-25% of its optimistic value.

The tidal streaming sites are the least well represented by the generic analysis outlined in this report. Most UK tidal streaming sites are 'open sea' sites, as opposed to the idealised 'narrowing channel' case which has been used as the generic tidal streaming case. The energy extraction at these sites has been limited by the prescribed tidal range change. It is possible that energy extraction might have a lesser impact on the tidal range for open sea sites than for narrowing channel sites. On the other hand, energy extraction from open sea sites is likely to change local tidal flow patters more significantly, and reduce the tidal velocities through the farm more than would be the case for a narrowing channel, which could mean that the economics are affected to a greater degree by energy extraction than is calculated using the generic methodology. Running the Black & Veatch 2011 model with no limit on tidal range increases the AEP base case estimate by c. 35% from c. 29TWh/y to c. 39TWh/y.

Given the potentially favourable economics of the Pentland Firth Deep site (notwithstanding the challenges and costs of grid connection), it is logical to investigate allowing a greater CoE increase, enabling a higher AEP. Optimising the Pentland Firth resource increases the base case UK total AEP by c.25% from c. 29TWh/y to c. 36TWh/y. The UK averaged CoE decreases by c. 10% from c. 20p/kWh to c. 18p/kWh.

The updated methodology gives a revised base case estimate of the technical resource of 29TWh, which is c. 60% higher than the 2005 Black & Veatch Phase 2 estimate (which was estimated as 18TWh with an overall P10/P90 error band of +/-30%). The P10/P90 error band using the updated methodology is +/-40% using statistical analysis of a number of scenarios. There remains high uncertainty in the resource associated with tidal streaming sites. The Pentland Firth base case AEP has increased by c. 40% from c. 8TWh/y in the Black & Veatch Phase 2 report to c. 11TWh/y.

To obtain an estimate of the practical resource (the fraction of the Technical Resource that remains after practical constraints) Carbon Trust and Black & Veatch[3] identified the other key constraints (with assistance from the Crown Estate and its MaRS GIS model) for each of the 30 sites. More than 100 constraints were initially investigated. The relevant constraints were treated either as exclusion zones or as restricted zones, and weightings were applied to the different constraints in the restriction zones. This analysis suggests that c. 70% of the technical resource is retained after these key practical constraints (excluding grid connection) are applied, and the UK's practical AEP is c. 20TWh/y. The associated UK averaged CoE increases to c. 21p/kWh.

The results obtained for the practical resource are shown in the table below (CoE with discount rate (d.r.) 15%).

	Total Practical resource	**Average CoE with learning**
	TWh/y	p/kWh
Pessimistic (P10)	10.3	45.2
Base (P50)	20.6	21.0
Optimistic (P90)	30.0	15.5

Certain caveats as to the accuracy of the parametric approach are still necessary. Most sites will obviously not be fully representative of the idealised representations of the three generic regimes, and many sites will be significantly different, for instance with all three regimes being present. In these cases, the parametric expressions will not be as accurate. The impact on power extraction levels if alternative flow pathways are available is one common example of a caveat that needs to be borne in mind. In such scenarios, which are not uncommon, the derivation of the technical tidal current energy resource in the parametric methodology is an upper bound on the power available for extraction from the tidal current energy resource (if one assumes the imposed technical resource restrictions [see footnote on page 5] are representative).

Energy removal from the system that is due simply to the presence of the TEC device itself has not been considered in detail in the analysis presented in this report. Future focus to reduce this wasteful use of the resource by improved support structure design and streamlining has the potential to significantly reduce this loss of useful energy that would otherwise be available for harvesting. Prescription of wake losses in large tidal current farms is another area that requires further research.

The assessment of grid accessibility (and the real cost of connection on a site by site basis) is a key potential constraint on UK's practical resource. This should be investigated further, to assist with prioritising key sites for future development.

It has been shown that one of the most significant sources of uncertainty in the results remains the actual underlying resource data used to conduct this analysis. Comparison between MEA and tidal diamond figures showed significant discrepancies which led to the large error bands derived for the final UK resource estimate (and economics). Further work to understand these discrepancies, and undertaking ADCP measurements (or public domain collation of previous measurements) at various sites, would be extremely beneficial in terms of mitigating this uncertainty.

[3] This assessment was undertaken with input from Entec, Carbon Trust.

1 GLOSSARY

a_0 – The maximum driving tidal head difference for a particular tidal system. As explained in Appendix C, the prescription of a_0 depends on the type of system considered (tidal streaming, resonant basin or hydraulic current).

ADP – Acoustic Doppler Profiler.

AEP – Annual Energy Production.

CoE – Cost of Energy.

Cp – Device coefficient of performance, i.e. mechanical efficiency at which the device extracts energy from the incoming flow.

d.r. – Discount Rate.

HAA – Horizontal Axis Axial flow turbine.

HAC – Horizontal Axis Cross flow turbine.

HC – Hydraulic current system.

MEA – Marine Energy Atlas.

MEC – Marine Energy Challenge.

Marine Energy Accelerator – Programme run by Carbon Trust, which partly funded this study.

MSL – Mean Sea Level.

PD – Power Density.

Practical Resource – The energy (which is a proportion of the technical resource) that can be harvested after consideration of external constraints (e.g. grid accessibility, competing uses such as MOD, shipping lanes, etc.). This level of assessment fundamentally requires detailed project design and investigation on a case-by-case basis. The practical resource is hence a proportion of the technical resource.

P_{max} – The maximum total mean power harvested across the tidal cycle considered for a specified tidal system.

Q_{max} – The mean of the local maximum volume fluxes (m^3/s) for a particular tidal system over the tidal cycle considered.

RES – Resonant (basin) system.

Total Resource – Total energy that exists within a defined tidal system.

Theoretical Resource – Maximum energy that can be harvested from tidal currents in the region of interest without consideration of technical, economic or environmental constraints.

Technical Resource – The energy that can be harvested from tidal currents using envisaged technology options and restrictions (including project economics) without undue impact on the underlying tidal hydrodynamic environment. The technical resource is hence a proportion of the theoretical resource.

Practical Resource – The energy that can be harvested from tidal currents using envisaged technology options and restrictions (including project economics) without undue impact on the underlying tidal hydrodynamic environment, and allowing for the impact of key external constraints excluding grid constraints (e.g. shipping, fishing, MOD etc.). The practical resource is hence a proportion of the technical resource.

The Farm Method – Extraction methodology used in most studies previous to the 2004/5 MEC study [2] and 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. This method was used as a comparator to the MEC Flux Method in the 2004/5 MEC study.

The MEC Flux Method – Extraction methodology developed in the 2004/5 MEC study [2] and 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.

The Flux Method – Extraction methodology developed in this study and based on the use of only the Total (energy) Resource. This is an evolution of the MEC Flux Method, intended to be more appropriate to different types of sites, but the method remains independent of the device type, efficiency and packing density. The method is explained in further detail in Appendix C.

The MEC Significant Impact Factor (%) - Developed in the 2004/5 MEC study [2], the MEC SIF represented the percentage of the kinetic energy flux that was deemed to be extractable by the MEC Flux Method without significant economic or environmental effect, to give the Technical Resource.

The Significant Impact Factor (SIF) (%) - In this study the SIF represents the percentage of the Total Resource that could be extractable without significant economic or environmental effect, to give one of the limits to the Technical Resource (the Farm Method providing another limit).

TEC – Tidal Energy Converter, a device which captures energy from tidal currents.

TS – Tidal streaming system.

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

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

V_{rated} (m/s) – Rated velocity of tidal stream device. Rated velocity is the velocity at which the device reaches maximum (rated) output.

2 SCOPE AND BACKGROUND

In 2004/5, as part of the Marine Energy Challenge (MEC), Black & Veatch (with input from University of Edinburgh) defined a ‘Significant Impact Factor’ (SIF) to estimate the UK’s ‘extractable tidal stream resource’ (the equivalent parameter is called the ‘technical tidal current resource’ in this report), representing the percentage of the total tidal stream resource at a site that could be extracted without significant economic, environmental or ecological effects [2].

Since the initial investigation, limited research has been reported on the SIF, although Black & Veatch and the University of Edinburgh have undertaken some specific site assessments. Due to various studies published since 2005 (e.g. the ABPmer study funded by Juice [3]), further work on understanding how to quantify the SIF (or extractable resource) at individual sites, as was recommended in Black & Veatch’s 2005 report, remained important.

Black & Veatch therefore applied for Juice funding in February 2008 to update previous work on the SIF. Due to budget constraints at Juice, the work reported in Appendix C was also partly funded by Carbon Trust, and the present report (funded by Carbon Trust) is an update of the MEC 2004/5 UK tidal stream resource reports.

3 SUMMARY OF UNDERLYING HYDRODYNAMIC MODELLING WORK

Appendix C summarises the underlying hydrodynamic modelling work that informs this report.

The focus of the work presented in Appendix C is the far-field response of the tidal system with regard to the economic and environmental implications of widespread, large-scale TEC (tidal [current] energy converter) deployment. For this study, hydrodynamic tidal models adapted to simulate the large-scale impact of various hypothetical levels of energy extraction were used to assess the response of idealised representations of generic tidal regimes. Additional modelling of several real tidal environments, as opposed to generic representation, was then used to undertake a partial validation of the generic results.

The work presented in Appendix C (and therefore within this Section 3) drew extensively on work carried out by Scott Couch at the University of Edinburgh (UoE), with additional input from Michael MacWilliams of River Modelling (USA); Black & Veatch mainly acted as 'project manager and client' to ensure the output of this work could be used to inform this 'UK Tidal Current Resource & Economics' which is an update to the equivalent 2005 report.

The original energy extraction test cases developed by UoE in 2004 using TFD-2D [1] were replicated by River Modeling using the UnTRIM standard industry model. The test cases demonstrated that the implementation of the energy extraction method within the UnTRIM model provided very similar results to the implementation within the TFD model. The validation provided confidence in the methodology and enabled its application to real world examples where the UnTRIM model (without energy extraction) has previously been very well validated.

For the purposes of examining the potential to develop a parametric model that can be applied across a range of sites in order to enable a national resource study, the approach adopted in Appendix C is to consider ideal representations of each of the (three) relevant hydrodynamic mechanisms which give rise to the tidal current conditions necessary for TEC deployment:

- Tidal streaming: Tidal streaming is the physical response of the tidal system to maintenance of the continuity equation; when a current is forced through a constriction, the flow must accelerate.
- Hydraulic current: If two adjoining bodies of water are out of phase, or have different tidal ranges, a hydraulic current is set up in response to the pressure gradient created by the difference in water level between the two bodies.
- Resonant system: Resonant systems occur as a consequence of a standing wave being established. A standing wave arises when the incoming tidal wave and a reflected tidal wave constructively interfere.

It is noted that this approach builds upon (and the later results are in general agreement with) work undertaken by several groups worldwide, e.g. [4].

This then enabled parameterisation of the response of each of the three representations to energy harvesting through TEC deployment. This is crucial because the three identified mechanisms potentially respond differently to various levels of energy extraction, which has not as yet been explicitly addressed in detail in existing research.

In all three tidal regimes, an upper *theoretical limit* was identified beyond which attempts to extract more energy from the system actually reduces the overall energy that is harvested. The demonstrable occurrence of a maximum mean power (P_{max}) for each domain and localised driving mechanism is of great practical value, as it indicates the existence of a theoretical extraction limit in a particular location using the TEC technology approach. This is indicative of a key component of tidal current energy resource dynamics – the existence of a theoretical tipping point beyond which the addition of additional extraction devices will harvest less overall resource due to the impact of the combined harvesting effort on the underlying tidal hydrodynamics. This highlights that the outdated 'farm' resource assessment methodology is fundamentally flawed, as first indicated in the 2004/5 MEC reports [2]. In each of the individual tidal regimes, there was good agreement on the theoretical maximum energy removal limit – which can be quantified with reference to the flow discharge in the undisturbed (natural) simulation case (Q_{max}) and the available driving head difference (a_0). The flow discharge, flow velocities and tidal range were all reduced by energy harvesting, as expected, and these effects would at some point have impacts on the environment and the project economics that would be unacceptable, as outlined in the 2004/5 MEC reports [2].

Consideration of arbitrarily prescribed 'environmentally and economically acceptable' impacts of energy removal on the overall tidal hydrodynamics of the system enables assessment of an 'acceptable' energy removal limit. Again, a common metric for determination of the *technical energy removal limit* was identified in each of the three cases, again related to Q_{max} and a_0.

As was previously hypothesised in the 2004/5 MEC reports [2], Appendix C demonstrates conclusively that the response of different generic regimes to energy harvesting, although demonstrating similar trends, is not consistent. This is summarised in the Table 3-1 below. The caveats raised in the discussion in Appendix C must be borne in mind when considering these results, as must the differing definitions of a_0.

Table 3-1 Theoretical and Technical Resource equations from Appendix C

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

Energy extraction was implemented in two real world models to provide confidence in the generic results obtained. A Strangford Lough case presented good to excellent agreement between detailed tidal hydrodynamic simulations and the simple parametric model derived from the generic cases.

Despite the lack of extensive testing, the combined numerical modelling analyses provide confidence in applying the key metrics identified for quantifying the *theoretical resource* equations in the final proposed parametric approach. There is also good confidence in the basis for the *technical resource* calculations, although the actual difference between the theoretical and technical resource is determined by the prescription of currently arbitrary (but reasonably informed) limits to the impacts. In a national or regional resource assessment, sensitivity testing of these arbitrarily prescribed limits is recommended, and different regions may well need to prescribe different 'base-line' limits due to different local environments. Clearly, consideration of the practical resource should consider acceptable limits to the impacts on a site-by-site basis, in conjunction with all the other aspects that would limit practical resource extraction.

Certain caveats as to the accuracy of the parametric approach are still necessary. Most sites will obviously not be fully representative of the idealised representations of the three generic regimes, and many sites will be significantly different, for instance with all three regimes being present. In these cases, the parametric expressions will not be as accurate. The impact on power extraction levels if alternative flow pathways are available is one common example of a caveat that needs to be borne in mind. In such scenarios, which are not uncommon, the derivation of the theoretical (and technical, if one assumes the imposed limits are representative) tidal current energy resource in the parametric methodology is an upper bound on the power available for extraction from the tidal current energy resource. Examples of such caveats include:

- Tidal systems where alternative flow channels are available [5]. Also see [6, 7].
- Channels where only a partial tidal fence (or array) is installed across the cross-section [8].
- The extreme case of a TEC device or small array in a theoretically (laterally) unbounded domain [8].

The other major issue requiring further consideration is the prescription of how much of the energy removal from the tidal hydrodynamic system can actually be ascribed to useful energy generation. Potential device coefficients of performance (Cp) and conversion efficiencies are of course fairly well understood, and best practice understanding of TEC device performance envelopes has been utilised in some of the key assumptions necessary in this analysis. However, the energy removal from the system that is due simply to the presence of the TEC device itself has not been considered in detail in the analysis presented in this report. Future focus to reduce this wasteful use of the resource by improved support structure design and streamlining has the potential to significantly reduce this loss of useful energy that would otherwise be available for harvesting. Prescription of wake losses in large tidal current farms is another area that requires further research.

Despite the clear agreement of the proposed parametric approach to much of the national and international literature, there are discrepancies with some existing literature:

- The ABPmer Juice-funded study [3] is one of the recent studies that have not understood the Significant Impact Factor as it was proposed during the MEC [2]. That study therefore does not actually account for the limitation intended to be imposed by the flux method, which was intended to ensure that deployment of TECs in multiple data cells did not result in over extraction of the available energy. In fact, the ABPmer study in essence simply used the historical farm method without the aggregation of the output data into farms as it only presented cell data. As a consequence, the ABPmer study predicted approximately five times more extractable energy than the 2004/5MEC study [2]. Given the above explanation, it is not surprising that the ABPmer prediction is similar to the farm method calculation presented in the 2004/5 MEC work and previous similar studies.

- Salter, most recently in [9], suggests that the tidal current energy resource available in the Pentland Firth should be at least an order of magnitude greater than identified in the MEC analysis. Minor reasons that the estimates differ include: (i) that Salter tends to quote peak power, whereas the power averaged over a tidal cycle is considerably lower, and (ii) the average velocity assumed by Salter for the entire Pentland Firth is higher than assumed in the MEC analysis. The critical difference is the value ascribed to seabed friction. Calculation of energy loss due to seabed friction is highly sensitive to the selection of the bed friction coefficient C_D. Values of C_D used in Salter's various estimates are typically around 0.02. This is not typical of values of C_D advocated in tidal hydrodynamic applications. More typical values of C_D referenced for tidal application are generally an order of magnitude smaller [10, 11]. Salter references a number of sources to derive his proposed value for C_D; however, many of these are not relevant to tidal hydrodynamic applications and the primary tidal hydrodynamic reference is for a very atypical site (as stated by the authors). Typical values of C_D actually used in various calibrated and validated hydrodynamic models of various UK and global sites that are representative of UK sites (including the Pentland Firth) correlate well with the existing literature referenced above [12]. Salter has suggested undertaking ‘surface slope’ measurements of the Pentland Firth using strings of ADCPs to calculate the seabed friction. However, the ‘surface slope’ of the Pentland Firth can be readily estimated from existing tidal height data, as has been undertaken for this work in order to derive a_0 which is required for each site. Analysis of this data also suggests that the typical values of C_D in the literature are relevant for the Pentland Firth. Tidal hydrodynamic modelling of the UK’s continental shelf (as proposed by the Energy Technology Institute) could assist in improving the current estimates of seabed friction across the UK and specifically for the Pentland Firth resource.

- Mackay [13, 14] starts by evaluating the instantaneous power available from the Atlantic in UK’s territorial waters. An overall average figure of 450GW [13] is proposed. Little attention is initially paid to the means of energy extraction. An arbitrary percentage is initially presumed to be extractable [13]. In [14], assessment of the UK territorial extractable resource is apparently based upon a return to the ‘farm’ approach to resource characterisation, as the author is unconcerned by the potential interaction between devices and cumulative effects of energy harvesting. This particular farm approach also takes in very large areas of low energy resource of limited economic value for tidal current energy development even in the long-term (e.g. V_{msp} values of c. 1.65 m/s), exacerbated by unrealistically extrapolating tidal current data over extensive areas.

4 THE BLACK & VEATCH 2011 MODEL

4.1 Site selection and configuration

4.1.1 Site selection methodology

The latest 2008 version of the Marine Energy Atlas (MEA) [15] was used as primary source of data for the 2011 UK tidal current resource assessment. Sites retained from the MEA source in this analysis feature a mean annualised power density in excess of 1.5kW/m^2 and a depth in excess of 15m (both criteria being met anywhere over the site areas considered) as we consider that these criteria are required for reasonable project economics (as is apparent from the later results). Black & Veatch acknowledges that technologies specifically designed for low power density sites (such as Minesto's technology, which was supported during the Marine Energy Accelerator) could potentially result in lower power density sites becoming economic; however, these are not considered in the analysis, due to a number of significant uncertainties.

When the MEA source data did not confirm a site previously identified by Black & Veatch in 2005 [2], i.e. the above two criteria are not met or no data is available at all (e.g., MEA spatial resolution too coarse), other available data sources were checked successively for the considered site, namely and in order: TotalTide, Tidal Stream Atlases and Pilot books.

Thirteen sites from the 2004/5 MEC reports [2] did not meet the 1.5kW/m^2 power density criteria and have therefore been ignored in the present 2011 study. These sites represented c. 5% of the 2004/5 Technical Resource. Four sites had a total mean annualised power in excess of 1.5kW/m^2 in the 2004/5 MEC reports [2] and were consequently taken into consideration in the 2011 resource assessment. However these sites, namely Dorus Mor, Orkney Papa Westray, Eday Sound and Yell Sound East Channel, were not retained in the 2011 study as no robust enough data could be sourced. Four sites that were not selected by the MEA screening analysis were added using data sourced from TotalTide, relevant Tidal Stream Atlases and Pilot books. These sites were Strangford Lough, Kyle Rhea, Yell Sound West Channel and Blue Mull Sound.

The Irish sites which appeared in the 2004/5 MEC reports [2] were also ignored, as they are not located within the UK territorial waters. Seven sites were ignored: River Shannon - Scattery Island, Inishtooskert Island, Dursey Sound, Dursey Head-The Cow, Dursey Head-The Calf, Mizen Head and Gascanane Sound. In the 2004/5 MEC reports [2], these sites only represented c. 0.5% of the Technical Resource.

Note that, for comparative purposes, the MEA data has been compared wherever possible with the data provided by the UK Hydrographic Office (UKHO) commercial tidal prediction software (TotalTide). On average and over the sites considered, the tidal diamond figures (TotalTide data) under-predict the resource, in terms of power density, by c. 45% with respect to the MEA. Based on recent site specific assessments involving ADP measurements, Black & Veatch believes that the MEA might under-predict the resource by up to 20% in some areas. An overall error band of -45% +20% has therefore been applied on the MEA resource data used in the Black & Veatch 2011 model.

4.1.2 Modifications in site configurations from the 2004/5 MEC reports [2]

The following three site configurations have been modified and differ from the 2004/5 MEC reports [2]:

- In [2] the Blue Mull Sound was split into two sites, North and South, but the lack of data has led to their combination in this report.

- The analysis of the MEA data has led to the combination of Westray Firth-Falls of Warness and Westray Firth-Kili Hom/Fers Ness which has become "Westray Firth".
- The Casquets site was divided in "East Casquets" and "West Casquets" as the MEA data exhibits two distinct areas of high intensity resource.

4.1.3 Site combinations

The whole Pentland Firth area has been considered as one site only, of the hydraulic current type. From a hydrodynamic point of view it is not practical to split the area into several smaller sites, although its size implies that it will be developed in phases. The 2011 Pentland Firth site therefore includes the following six sites identified in 2005: Hoy, S. Ronaldsay, Stroma, S. Ronaldsay/ P.Skerries, Pentland Skerries, Duncansby Head. Note that, in order to match the real development that is currently being planned in shallow areas of the Pentland Firth, Black & Veatch considered a 600MW rated farm to be deployed in the shallow (<35m MSL) areas of the Pentland Firth in the near-term (see Section 4.3.3), before the entire site is later developed (which is assumed to be in one phase).

The two sites Islay and Mull of OA identified in 2004 have been counted as only one site in the 2011 study, "Islay/Mull of OA", as they appear to be on the same energy flux line. The new "West Islay site" is a combination of two areas of high intensity resource which appear in the MEA. Note that, even though Islay/Mull of OA and West Islay are close together, they are not considered as a double-counting as they do not appear to be on the same energy flux line.

Note finally that Carmel Head, which was added in the 2005 MEC report [2], has been extended as it now covers three hot spots in the MEA.

4.2 Techno-economic model build-up and operation

The methodology used by Black & Veatch to carry out the 2011 assessment of the UK tidal current resource and the associated economics of energy extraction is detailed in Figure 4-1 and each step is then described in more detail in the section below.

Note that all Cost of Energy (CoE) results are calculated using a 15% discount rate and are based on 2009 costs.

In summary, the following steps are employed:

Step 0: In step 0 the farm method is first utilised to derive a theoretical tidal current farm that is optimised for CoE assuming the MEA power density is available (despite the reduction due to energy extraction).

Step 1: Step 1 then calculates how much the power density and velocities at the site can decrease before reaching a specified CoE limit.

Step 2: In step 2 all the parameters in the farm calculations are adjusted to account for the specified tidal range and velocity limits and the CoE limit.

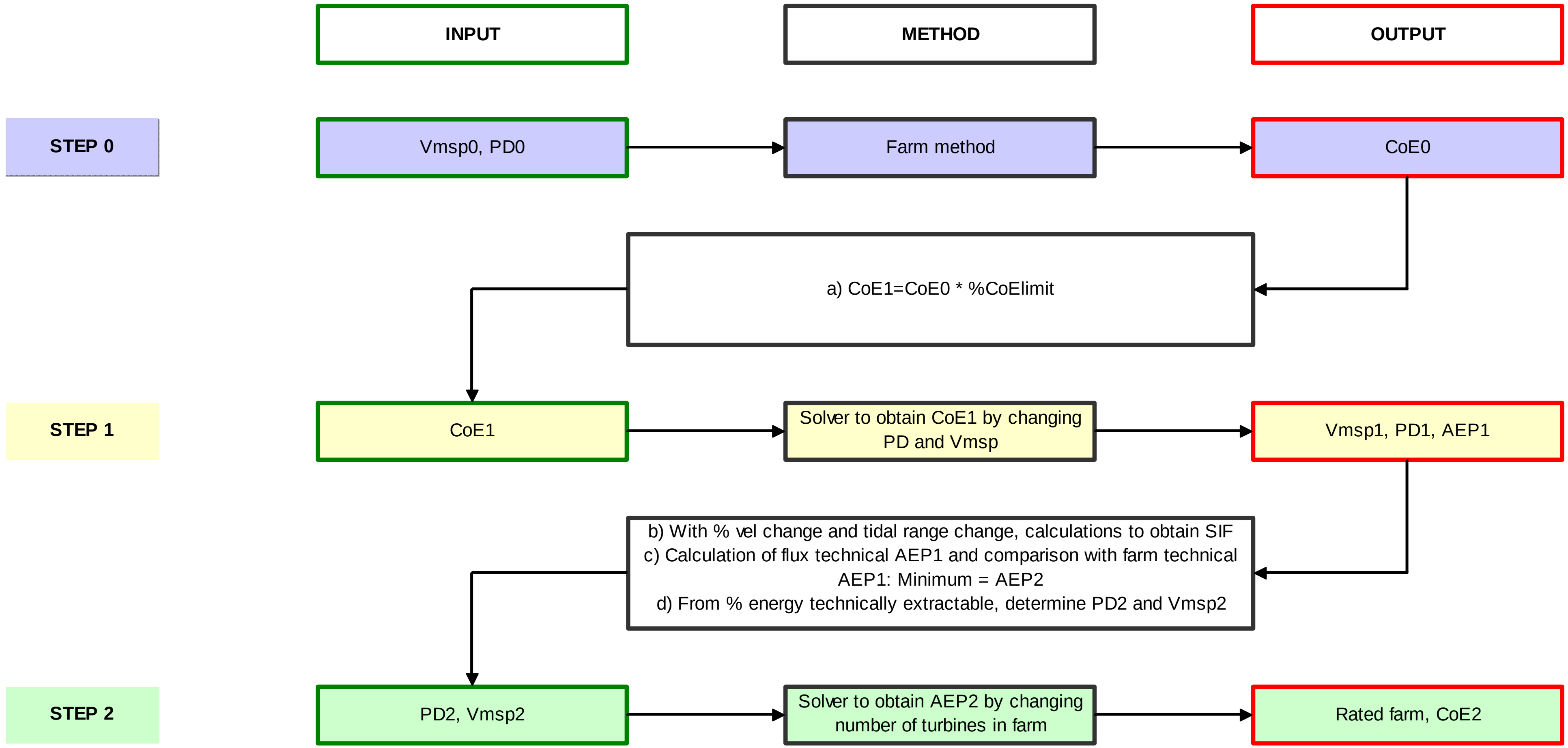

Figure 4-1 Model build up and operation

4.2.1 Step 0

4.2.1.1 Input data

The input data for each site (depth, power density (PD_0), $Vmsp_0$, area) was obtained as described in section 4.1.

4.2.1.2 Method: Farm method

Black & Veatch created a techno-economic model to initially optimise CoE, using the farm method. This model relies on various underlying assumptions, as detailed in the points below.

a) Clearance

As recommended in the EMEC standard, a top clearance of 5m has been considered. A bottom clearance of 25% of the depth has been applied.

b) Spacing and number of turbines

In the farm method a spacing of 2.5d by 10d is used, as recommended in the EMEC standard. This is directly equivalent to 1.25d by 20d, as suggested by the University of Southampton [16].

c) Capex and Opex costs

The underlying costs and scaling parameters used in the Black & Veatch 2011 model were derived from work undertaken by Black & Veatch in the Marine Energy Accelerator. The '1st generation technology' costs (without learning) are expected to be representative of first commercial farm costs (demonstration farm cost premiums and early financial premiums are excluded), and are based on technology that is already largely proven.

A '2nd generation technology', which is based on the 1st generation technology but represents a step-change economic improvement rather than incremental learning (e.g. its swept area might be much larger for a similar support structure and installation cost, see also comments on learning rates in Section 4.3.6) is assumed to become available and is used in the model from the Pentland Firth Deep site onwards (see Section 4.3.3 for the deployment sequence). These 2nd generation costs (without learning) are deemed to be representative of first 2nd generation commercial farms after learning has applied on the 1st generation sites (i.e. all sites developed before Pentland Firth Deep is developed). It should be noted that if such 2nd generation technologies are not developed successfully, then CoEs for Pentland Firth Deep, and all later sites, could be expected to be substantially higher (c. 20%+).

Grid connection costs only include initial high level estimates of the costs of connection to a shore based transformer/grid connection station. No upgrades of the distribution or transmission network, or system use charges are included, as these cannot be estimated on a generic basis. These costs could be significant for sites that are remote from the present grid network, or where the grid is weak, or ongoing transmission capacity is limited. Pentland Firth is a notable example of such a site.

The error bands applied on CoE for the 1st generation technology, due to inherent uncertainty on Capex and Opex estimates (the uncertainty in CoE due to all model parameters is fully addressed in Section 4.5.2), has been assessed based on a full Monte Carlo analysis of the underlying uncertainties, assuming various generic site parameters. An overall error band of -10% +20% has been applied on the CoE for the 2nd generation technology deployments.

d) Optimisation of rated power and turbine diameter

The optimisation of the technologies in terms of CoE – based on optimisation of rated power and turbine diameter, could only be carried out using a simple two constituent tidal model for each site. This simple model enabled the determination of the Annual Energy Production (AEP) figures for each site solely from the mean annualised power density from the MEA. However, this only provides satisfactory outcomes if the power density from the MEA matches that from the two constituent model, which is initially driven by the Vmsp and Vmnp from the MEA. This match was achieved by slightly modifying the MEA's Vmsp and Vmnp at each site.

In order to develop as realistic a model as possible, Black & Veatch also believes that rated power and diameter should not be fully optimised by the model. It is highly unlikely that developers will create site specific devices, but rather *classes* of devices, as it is the case in other renewable energy sectors. Only two rated velocities and 5 diameters (10, 15, 20, 25, 30m) have therefore been allowed within the model, i.e. there are ten rated powers available within the model. The rationale behind the two rated velocities is shown in Figure 4-2: one can clearly see two groups of sites emerging from the UK's main potential sites: most sites feature a hub height Vmsp between 2.25m/s and 2.50m/s whereas other sites' hub height Vmsp varies between 2.9m/s and 3.1m/s. Only two sites, both of which are relatively small, differ notably from the others (Kyle Rhea and Strangford Lough). The power density data presents a very similar pattern.

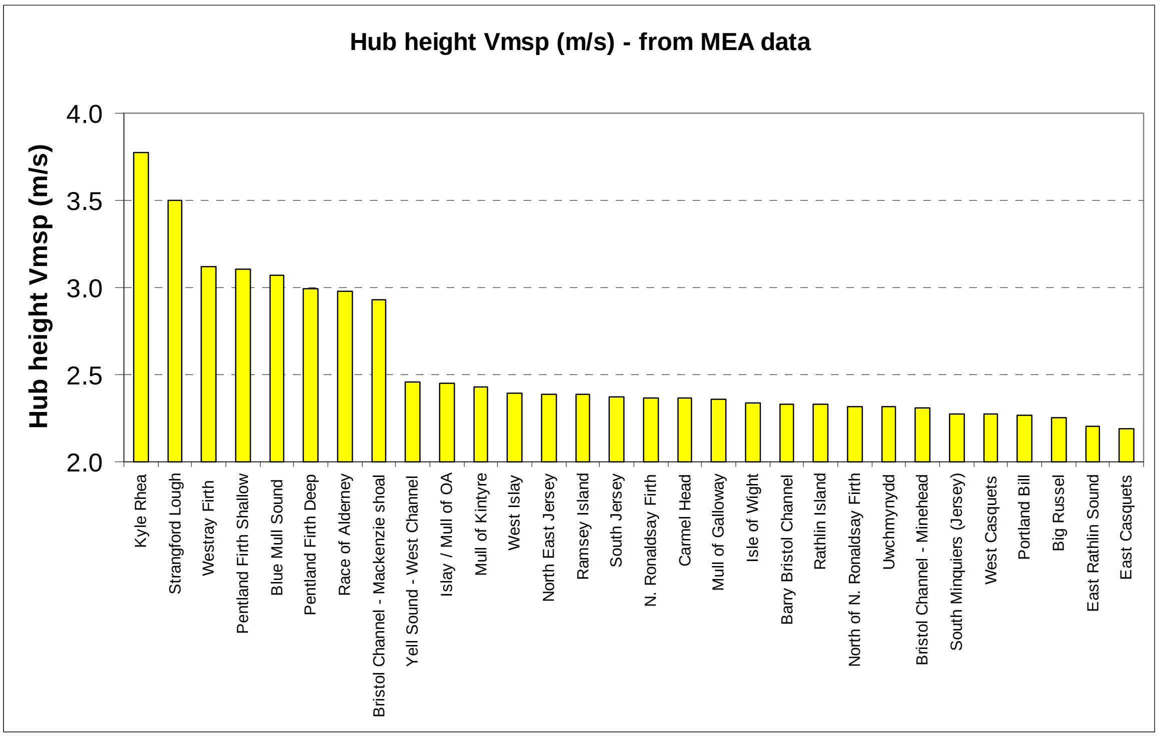

Figure 4-2 Hub height Vmsp data by site (MEA data)

This optimisation is part of the Step 0 in the diagram. Note that the optimised parameters are re-calculated at step 2 with the updated Vmsp and power density after energy extraction effects.

4.2.1.3 Between step 0 and step 1(a)

Step 0 calculates an initial CoE using the farm method for each site. A potential increase in CoE is then applied to this CoE_0, to obtain to a potential CoE_1 limit for each site. The percentage increase in CoE which is deemed to be acceptable ("%CoE limit") is based solely on economic considerations, and a 20% value has been considered in the base case. The "%CoE limit" varies between 10% in the pessimistic case and 50% in the optimistic one.

4.2.2 Step 1

4.2.2.1 Input

For each site, the only new input value is the potential CoE_1 limit obtained above. All the other parameters used in the model are still set as in step 0.

4.2.2.2 Method

The aim of step 1 is to understand how much the power density and velocities at the site can decrease before having too great an impact on the economics of the project. To obtain the acceptable decrease in power density and Vmsp, a solver is run for each site in the model to obtain the CoE_1 limit identified above - by changing power density and Vmsp. The output is hence new values, PD_1 and $Vmsp_1$ with which the limiting CoE_1 is reached.

4.2.2.3 From step 1 to step 2

a) Calculations to obtain new SIF value

From the UoE results obtained for each type of site, figures showing the energy extraction limit for each type of site as a function of the acceptable tidal range alteration and mid-range velocity alteration (derived from the acceptable CoE increase) have been created. This data is used in the economic model to obtain the "new SIF", i.e. the percentage of energy technically extractable with acceptable reductions of mid-range velocity and range.

Figure 4-3 to Figure 4-5 below show the data for the 3 types of site, with the input parameters similar to the ones used by UoE as an example. The % of energy technically extractable is given in red and matches the results found by UoE as given in Table 3-1.

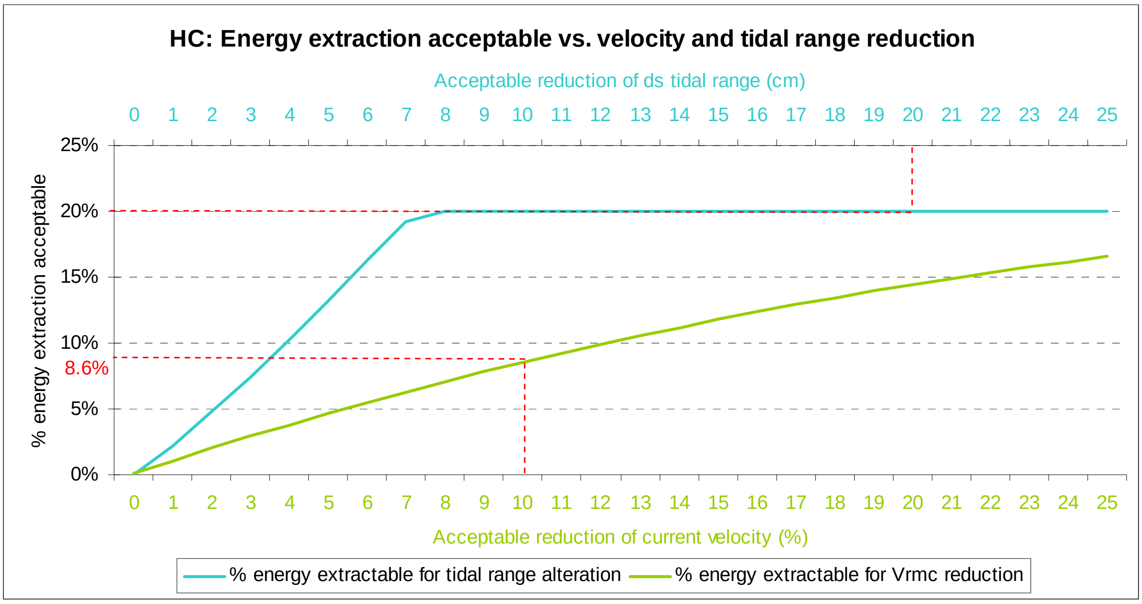

Figure 4-3 Energy extraction vs. velocity and tidal range reduction for Hydraulic Current sites

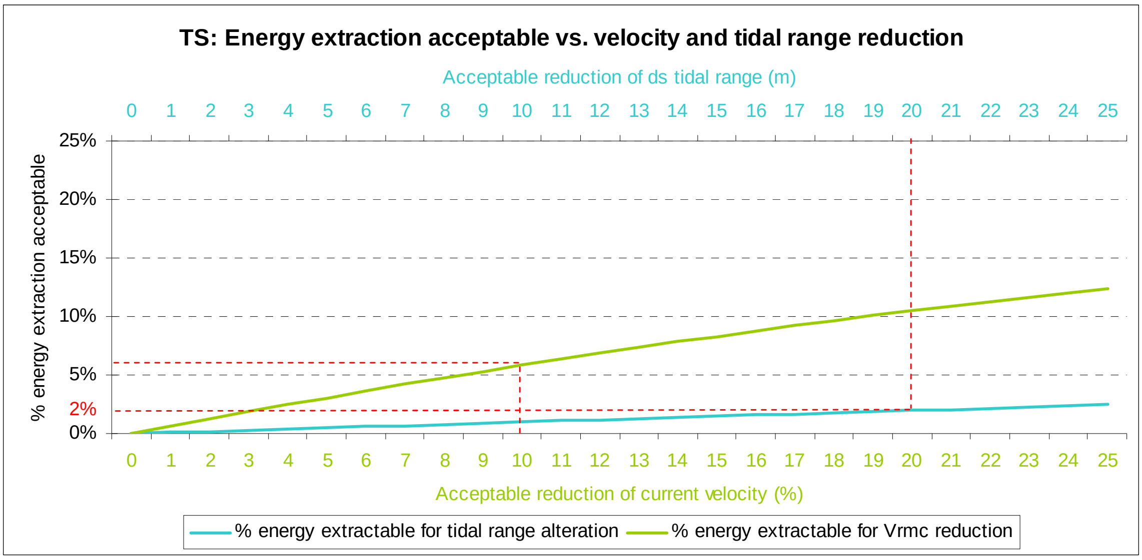

Figure 4-4 Energy extraction vs. velocity and tidal range reduction for Tidal Streaming sites

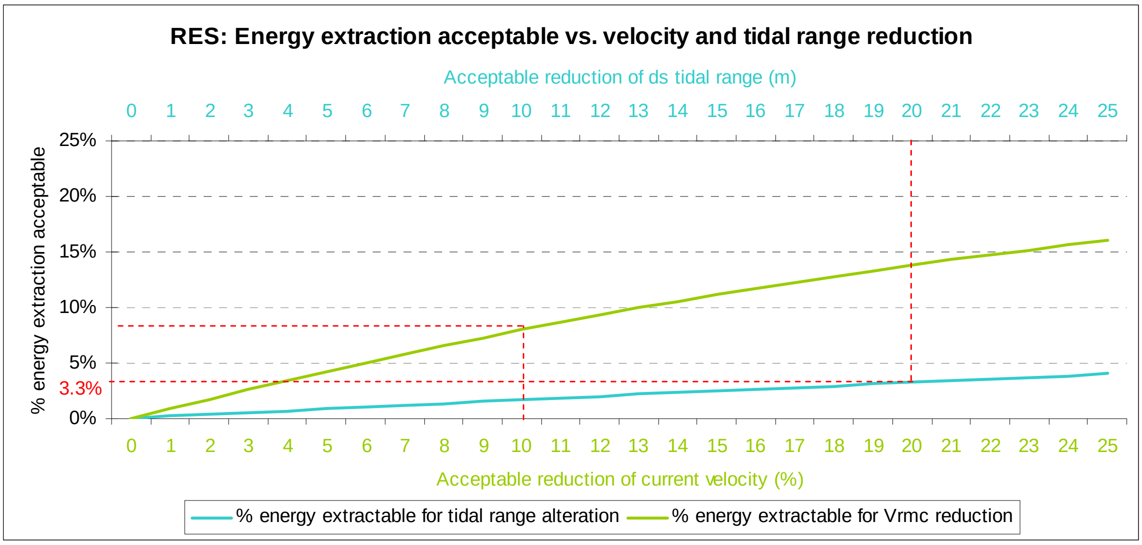

Figure 4-5 Energy extraction vs. velocity and tidal range reduction for Resonant Basin sites

b) Calculations to obtain the technical flux AEP

For each site, the SIF value obtained above is multiplied by the total energy available in the respective system (which is calculated following the method explained in Appendix C) to obtain the technical flux AEP_1 at each site. This value is compared for each site to the technical farm AEP_1 (obtained at the end of step 1), and the minimum of the technical flux and the technical farm AEP_1 is retained as the technical resource AEP_2.

c) Calculations to obtain final power density and velocity

AEP_2 allows determination of the percentage of energy that can be technically extracted from the system. For most of the sites, the constraint is either the tidal range limit or the farm method; this means that the CoE limit set between step 0 and step 1 is not reached for most sites in the base case. The velocity and power density reductions are calculated, and set as PD_2 and $Vmsp_2$.

4.2.3 Step 2

4.2.3.1 Input data

The input data are PD_2 and $Vmsp_2$ obtained from step 1.

4.2.3.2 Method

The aim of the step 2 is to adjust all the parameters in the farm calculations to the findings of the step 0 and step 1 which take into account the flux limit and other constraints. The economic model is hence run with the AEP_2 limit, the PD_2 and the $Vmsp_2$, and a solver is run with these parameters to find the number of turbines (along with their new characteristics, which are again optimised) required to reach AEP_2. The results are the final AEP_2 and CoE_2 for each site with parameters that have been adjusted to take into account the impact of energy extraction.

4.3 Key assumptions

The key assumptions used in the model are discussed below.

4.3.1 Technologies

As explained in Section 4.2.1.2, the Black & Veatch 2011 model has been based on front-running HAA devices, both 1st and 2nd generation. It is to be noted that shallow sites (c. 15m deep) feature a relatively high CoE as the 1st generation HAA technology is not as suitable for shallow sites as other technologies could be (e.g. HAC turbines and oscillating hydrofoils). As there was no robust cost and performance data available to this study for either HAC or oscillating hydrofoils, there was no alternative but to use HAA technology costs and performance. However, to mitigate the impact of this approach for the shallowest sites, we have allowed the HAA rotor diameter to be 10m even for sites with a depth of only 15m.

4.3.2 Distances to shore

The distance to shore for each site has been estimated at a high level using the Marine Energy Atlas. The distance to shore is integral to the calculation of the cable costs, but for the high capacity farms outlined in this report the distance to shore has a limited effect on the overall CoE.

4.3.3 Deployment sequence

Based on the CoE_2 figures, Black & Veatch ranked the UK sites and created a deployment sequence enabling learning rates to be applied, see Section 4.3.6. The shallow sites that are known to be under development are assumed to be developed first with 1st generation technologies. All remaining sites, starting from "Pentland Firth Deep", are assumed to then follow, in ascending CoE_2 order, developed using 2nd generation technologies.

The resulting site deployment sequence is shown in Table 4-1

Order of deployment	Sites	Area	Mean Sea Level (MSL)	CoE based on technical resource, no learning	Type of site
		km^2	m	p/kWh, dr15%	
1	Kyle Rhea	1	34	21	TS
2	Strangford Lough	3	35	25	HC
3	Pentland Firth Shallow	20	30	24	HC
4	Westray Firth	22	27	35	TS
5	Race of Alderney	68	31	26	TS
6	Pentland Firth Deep	240	62	17	HC
7	Blue Mull Sound	2	35	21	TS
8	Mull of Kintyre	9	116	23	TS
9	Ramsey Island	18	42	25	TS
10	Islay / Mull of OA	128	37	25	TS
11	Rathlin Island	4	102	25	TS
12	East Rathlin Sound	2	45	27	TS
13	Carmel Head	50	38	29	TS
14	Yell Sound - West Channel	2	30	32	TS
15	Bristol Channel - Minehead	17	30	34	RES
16	West Islay	93	31	36	TS
17	Big Russel	1	36	36	TS
18	North of N. Ronaldsay Firth	11	39	38	TS
19	Bristol Channel - Mackenzie	4	22	40	RES
20	Isle of Wight	21	29	57	TS
21	Uwchmynydd	1	29	57	TS
22	Mull of Galloway	9	29	59	TS
23	Barry Bristol Channel	9	26	60	RES
24	West Casquets	16	23	61	TS
25	Portland Bill	1	29	61	TS
26	East Casquets	61	22	62	TS
27	North East Jersey	35	21	72	TS
28	N. Ronaldsay Firth	17	17	74	TS
29	South Jersey	60	20	75	TS
30	South Minquiers (Jersey)	11	16	90	TS

Table 4-1 Site deployment sequence

For many sites, high tidal current velocities will be the result of the combination of two or more of the generic mechanisms (TS: tidal streaming, HC: hydraulic current, RES: resonant system). This is particularly true for many open sea sites, which have been classified as TS with a high level of uncertainty (see Section 4.5.2.2 for further discussion).

4.3.4 Environmentally acceptable velocity and range limits

For the purpose of this analysis, a 10% reduction in mid-range flow velocity or 0.1m reduction in tidal amplitude (0.2m reduction in tidal range) were considered as being the notional limits of environmental sensitivity. Ecological systems encountered at sites of high tidal current energy density are deemed to remain relatively unaffected by small changes in mid-range velocities of the order of 10%: these systems are inherently accustomed to high variability in local tidal stream velocity and sedimentation is unlikely to be an issue as most suitable sites feature a relatively rocky type of seabed[4]. Based on previous knowledge and experience, the notional limit of tidal range sensitivity was conservatively set to 0.1m reduction in tidal amplitude (0.2m reduction in tidal range) or 5% of the mean spring range value, whichever gives the minimum figure. For simplification, the 0.2m notional tidal range limit is used in the base case. The maximum tidal range alteration has been has been considered as 0.1m in our pessimistic scenario and 0.5m in our optimistic scenario. The 10% environmental limit on velocity change discussed above is not generally reached as the tidal range or economic constraints occur first. When the Pentland Firth sites are optimised in both AEP and CoE (see Section 4.5.2.3) the estimated change in velocity (18%) exceeds the arbitrarily prescribed environmental limit of 10% (however, the tidal range change is estimated to be only 5cm).

4.3.5 Economically acceptable velocity change

A key parameter of the 2011 Black & Veatch techno-economic model is the 'acceptable' increase in CoE at each site (% change and/or threshold) due to velocity reductions caused by large-scale deployments, and feedback of this site specific economic constraint to the technical resource. For the purpose of this analysis, this acceptable increase of CoE has been chosen as 20% in the base case, 10% in the pessimistic scenario, and 50% in the optimistic scenario.

4.3.6 Learning rates

This section provides an overview of learning experience from other similar developing industries and suggests applicable learning rates for tidal stream technology, and then considers a number of future scenarios for future generation costs.

In order to form a judgement as to the likely learning rates that can reasonably be assumed for the coming years it is appropriate to first consider empirical learning rates from other emerging renewable energy industries.

Figure 4-6 shows learning rate data for a range of emerging renewable energy technologies.

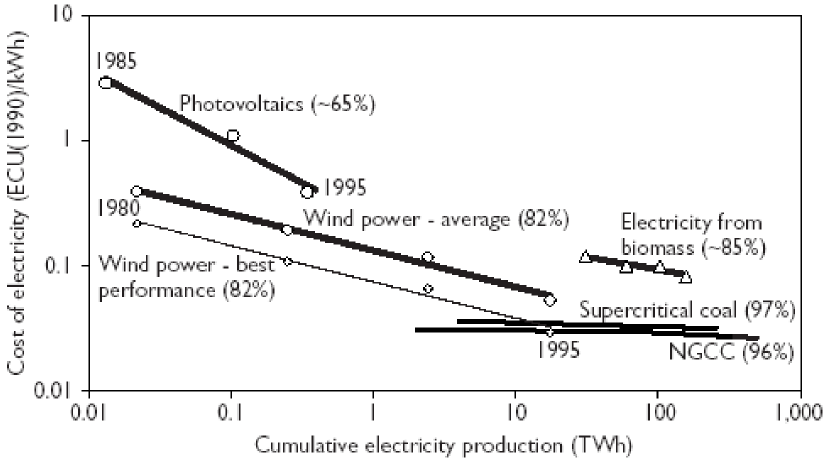

Figure 4-6 Learning in renewable energy technologies (IEA)

Price and cumulative capacity are observed to exhibit a straight line when plotted on a log-log diagram and mathematically this straight line indicates that an increase by a fixed percentage of cumulative installed capacity gives a consistent percentage reduction in price. For example the progress ratio for photovoltaics over the period 1985 to 1995 was ~65% (learning rate ~35%) and that for wind power between 1980 and 1995 was 82% (learning rate 18%).

[4] For further discussion of this aspect, see Section 4.3.5.2 of the 2005 MEC report.[1]

Any discussion as to the likely learning rates that may be experienced by the tidal stream industry will be subjective. A progress ratio as low as wind energy (82%) is not expected by Black & Veatch for the following reasons:

a) In wind, much of the learning was a result of doing "the same thing bigger" or "upsizing" rather than "doing the same or something new". This has probably been the single most important contributor to the progress ratio for wind, contributing c. 7% to the 18% learning rate. Tidal turbines, similarly to wind turbines, will benefit from increasing rotor swept areas, until the maximum length of the blades, limited by loadings, is reached. However, unlike for wind power, the ultimate physical limit on rotor diameter can also be imposed by cavitation or limited water depth, the latter being particularly important for the relatively shallow sites of (25-35m) that are likely to be developed in the near-term.

b) Much of the learning in wind power occurred at small scale with small scale units (<100kW), often by individuals with very low budgets. Tidal stream on the other hand requires large investments to deploy prototypes and therefore requires a smaller number of more risky steps to develop, this tends to suggest that the learning will be slower (and the progress ratio higher).

c) In the wind industry, the agreed technical solution has consolidated. Tidal stream technologies also appear to be converging on a horizontal axis turbine; however, a number of alternative concepts are still being developed. This indicates that learning rates will be lower (than would be expected) when measured against cumulative industry capacity.

Black & Veatch believes that a likely range of learning rates for the tidal energy industry in the UK is between 8-16% with a mid range value of 12%; this is c. 6% lower than that experienced in wind energy. However, as discussed in Section 4.2.1.2, the implementation of 2nd generation technologies is assumed to create a step-change in CoE at a certain point in time, offsetting the lower assumed incremental learning rate that is a result of the issues considered above.

4.3.7 Drag losses to structure and wake losses

The other major issue requiring further consideration is the prescription of how much of the energy removal from the tidal hydrodynamic system can actually be ascribed to useful energy generation. Potential device coefficients of performance (Cp) and conversion efficiencies are of course fairly well understood, and best practice understanding of TEC device performance envelopes have been utilised in some of the key assumptions necessary in this analysis. However, the energy removal from the system that is due simply to the presence of the TEC device itself has not been considered in detail in the analysis presented in this report. Future focus to reduce this wasteful use of the resource by improved support structure design and streamlining has the potential to significantly reduce this loss of useful energy that would otherwise be available for harvesting. For the purpose of the present resource/economics study, Black & Veatch assumed the percentage of energy wasted through the presence of the TEC device itself is between 5-25% of the total amount of energy extracted from the system, with a mid range value of 15%.

Another area requiring further research is the prescription of how much energy is lost due to wake propagation between rows of turbines. At model step 0, see Figure 4-1, the Black & Veatch model assumes a farm packing density of 1 rotor per $25D^2$ m^2, where D represents the rotor diameter. This is equivalent to spacing the rows 20-diameters apart in the downstream direction and 1.25-diameters apart in the lateral direction. This concurs with existing research being carried out on the subject [16, 17]. Both layouts have benefits and drawbacks and it is assumed that either could be representative. For the purpose of the present resource/economics study, Black & Veatch assumed the percentage of energy not captured by the turbines due to wake turbulence propagation is between 5-20% of the total amount of energy extracted from the system, with a mid range value of 10%. It may be possible to modify the farm packing density to enhance the response of the hydrodynamic tidal system [18], but this is not considered in detail as it remains an emerging science. In our optimisation of CoE by changing the output of the farm (which has the effect of changing the farm packing density), this new approach has been partially considered.

4.4 Pentland Firth example

The method described in Section 4.2 is detailed in this section for the Pentland Firth (Deep) site, with each intermediate result shown in Figure 4-7 to allow a better understanding of the process.

Pentland Firth is a hydraulic current case whose resource assessment is limited by the Flux method, for economic reasons, i.e. a 20% CoE increase limit in the base case. In such a case, CoE_1 is c. equal to CoE_2 and step b) and d) give the same percentage of resource extracted. The reason why it is not the case lies in the fact that, as explained in Section 4.3.7, some of the energy is lost due to drag around the structure. The difference between steps b) and d), i.e. 7.2% and 8.3% corresponds to the energy being lost by the system but not extracted by the turbines farm.

Note that the CoE figures given in Figure 4-7 do not account for any learning.

Note that the flux technical AEP_1 has been derived using the results provided in Table 3-1 and the following data, derived from the MEA and/or the Pentland Firth nautical chart:

- Width of site (flux line): 10,217m;
- Averaged depth on the flux line: 58.1m;
- Depth-averaged Vmsp on the flux line: 3.4m/s;
- a_0: 1.2 (coefficient a0 as defined in Appendix C).

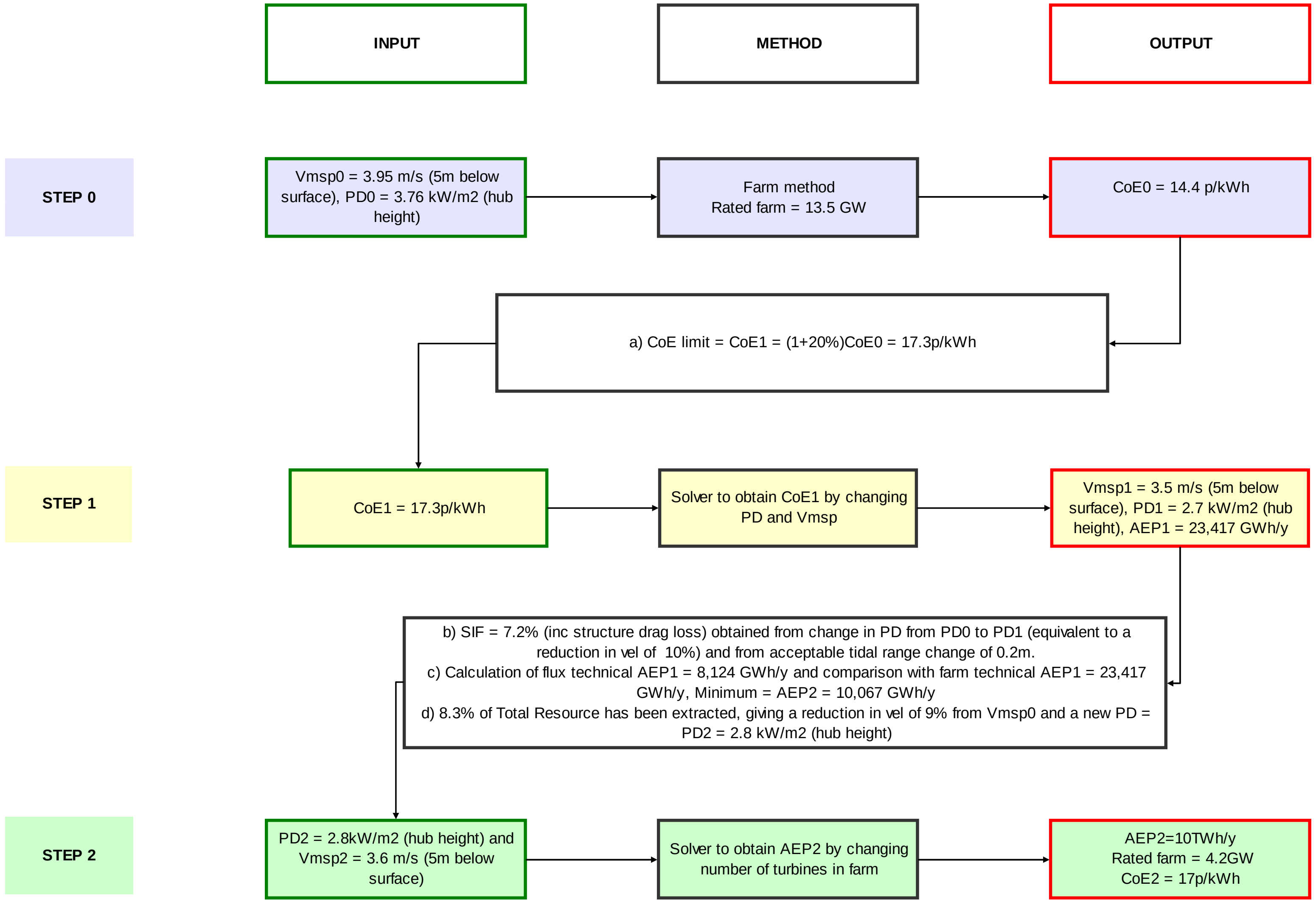

Figure 4-7 Model build up and operation: Pentland Firth example

4.5 Results and analysis

4.5.1 Black & Veatch 2011 model: Base case results

The Black & Veatch 2011 base case model results are presented in Figure 4-8, Figure 4-9 and Figure 4-10.

Figure 4-8 shows the CoE for each site considered in this study. The site sequence follows the assumed deployment scenario as discussed in Section 4.3.3. The white bars on Figure 4-8 refer to the CoE_0 obtained as an output of step 0, which is the CoE obtained following the original farm method. The green bars refer to the CoE obtained once the model has run with all base case parameters (see Section 4.5.2 for the uncertainty analysis). The orange bars refer to the CoE obtained once learning has been applied on the base case model results. The CoE of the last ten sites appears to be relatively high in comparison to the others. This is mainly due to the shallowness of these sites and other technologies that are under development (HAC turbines or oscillating hydrofoil devices) could make them more economically viable than shown.

Figure 4-9 shows the AEP figures for each site and with respect to the UK total, in the base case. Note that this data is presented by technical resource magnitude, not the assumed site development sequence. Pentland Firth Deep accounts for c. 35% of the resource, Race of Alderney for c. 8%, Carmel Head, South Jersey and East Casquets each for c. 7%. All the remaining sites all account for less than 5% of the UK total.

The resource-cost curve presented in Figure 4-10 represents the combination of the above two results. The curve has been obtained after averaging the cost-resource results of several sites:

- “Sites currently in development”: Kyle Rhea, Strangford Lough, Pentland Firth Shallow and Westray Firth;
- “Most attractive shallow sites with 1st generation technologies”: Race of Alderney;
- “Pentland Firth (deep) with 2nd generation technologies”: Pentland Firth Deep;
- “Attractive deep sites”: Blue Mull Sound, Mull of Kintyre, Islay / Mull of OA, Rathlin Island, Ramsey Island, East Rathlin Sound, North of North Ronaldsey Firth, Carmel Head, West Islay, Big Russel, Yell Sound - West Channel, Bristol Channel Minehead, Bristol Channel – Mackenzie Shoal;
- “Less attractive sites with 2nd generation technologies”: all remaining sites.

Note that, as explained in Section 4.5.2, an overall error band of c. -25% +115% has been applied on the CoE data obtained from the model runs.

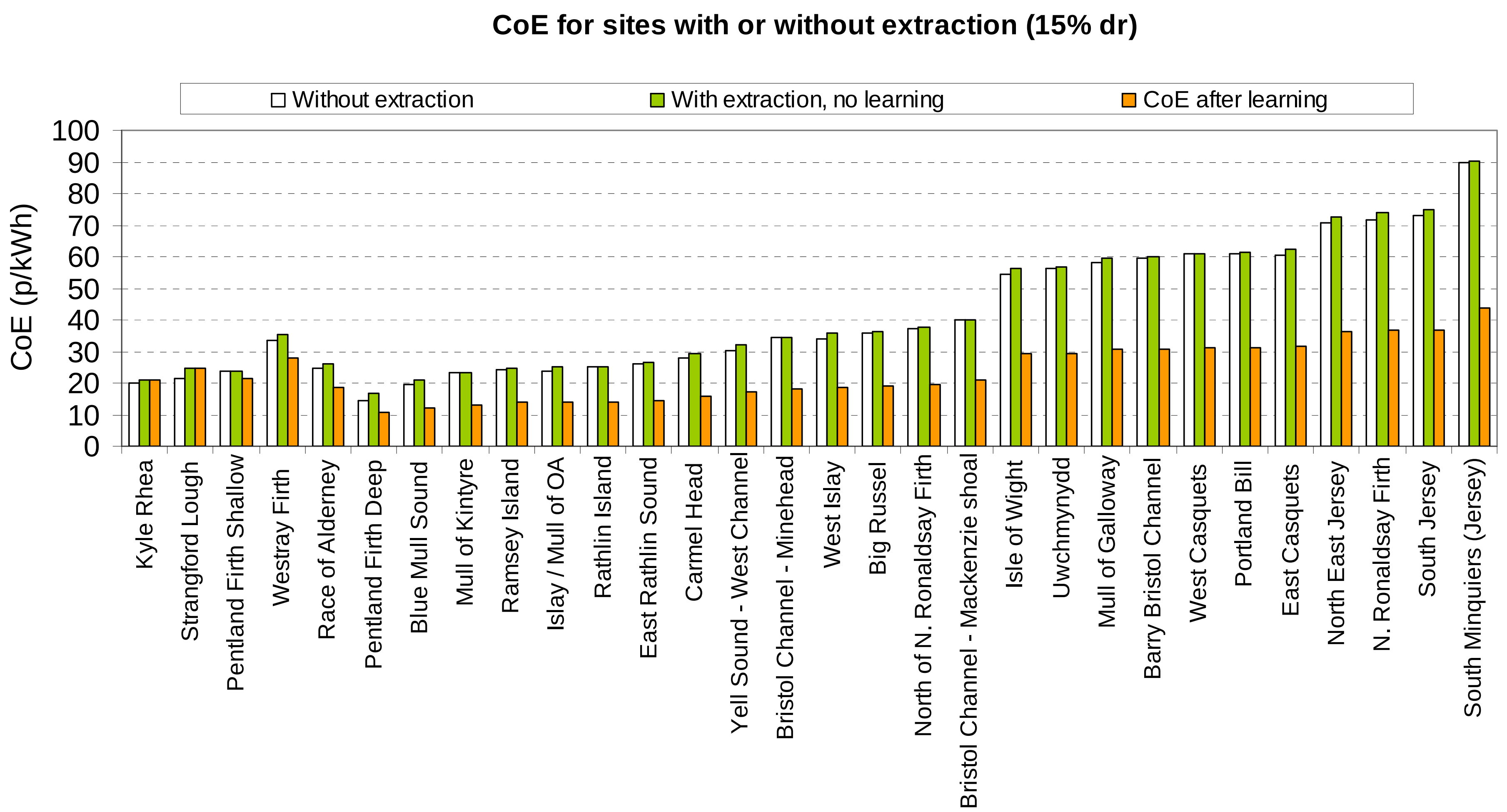

Figure 4-8 Black & Veatch 2011 base case model results: Cost of Energy (CoE error bands not shown, see Section 4.5.2)

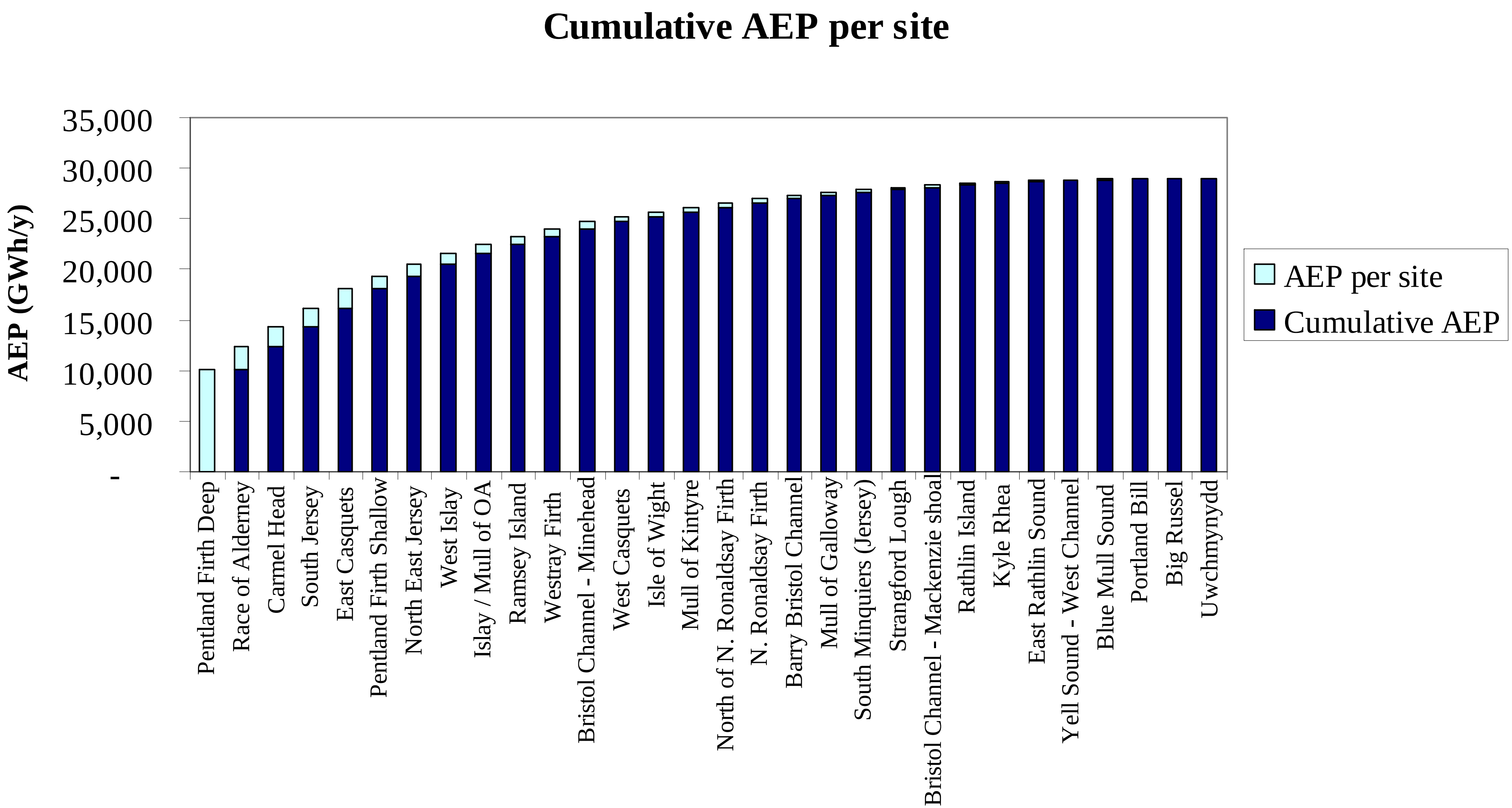

Figure 4-9 Black & Veatch 2011 base case model results: Annual Energy Production

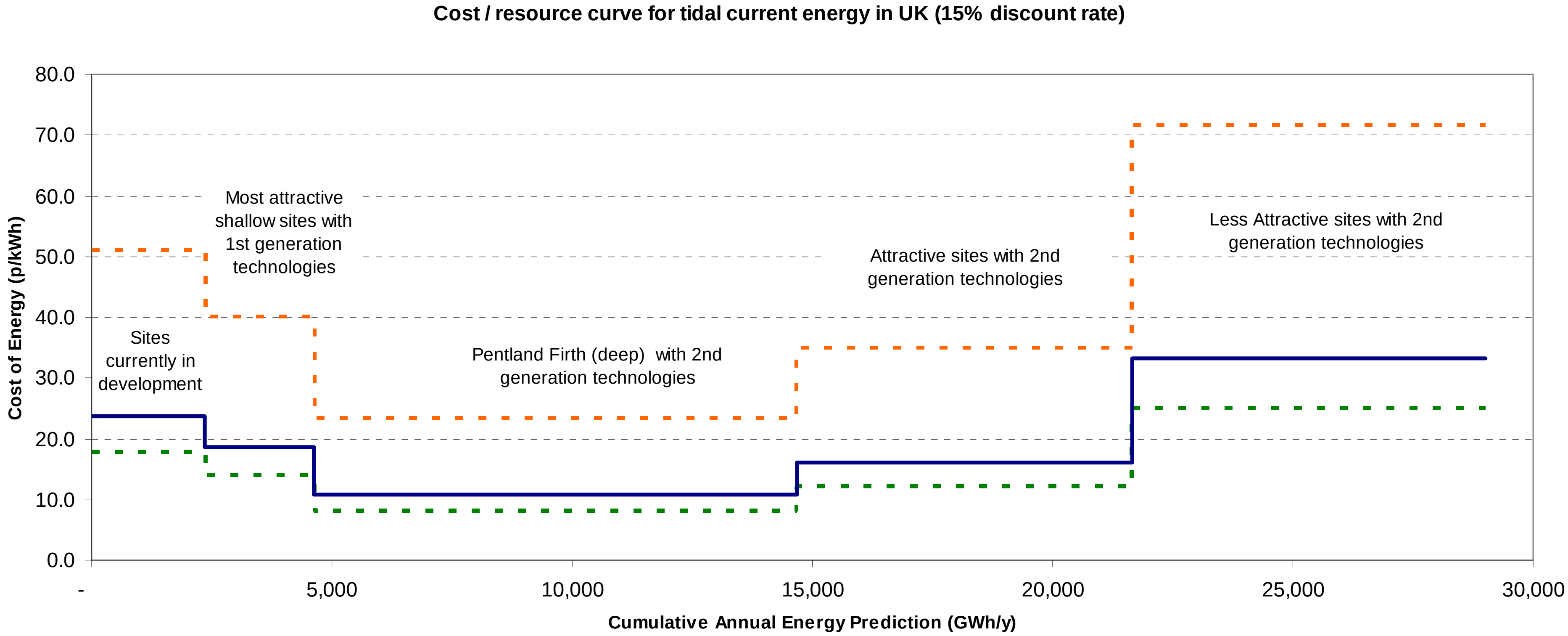

Figure 4-10 Black & Veatch 2011 base case model results: Cost-Resource curve (error bands shown only for CoE, see Section 4.5.2)

4.5.2 Sensitivity analysis

4.5.2.1 General results

This section highlights the effect of each key parameter used in the model on the overall UK AEP and averaged CoE. Each parameter has been assessed independently from the others. Standard statistical analysis has been used to derive final error bands on total UK AEP and UK averaged CoE. The overall results are shown in Table 4-2. Note that the UK averaged CoE has been obtained after averaging all CoE weighted by their AEP. Table 4-3 provides an overview of all sensitivities run in the Black & Veatch 2011 model. The uncertainties due to the cost data used to derive the CoE figures are technology specific and are explained in Section 4.2.1.2.

The most influential parameter on the pessimistic CoE figure is the actual resource data used to assess the sites, due to the significant uncertainty prescribed to the MEA data (see Section 4.1.1). All parameters have a similar influence on the optimistic CoE figure, see Figure 4-11.

Figure 4-12 shows that CoE and tidal range limits are the most influential parameters on the AEP, each influencing the AEP estimate to within c. +/-25% of its optimistic value.

Table 4-2 UK Technical resource AEP and CoE results

	Total Technical resource	**Average CoE with learning**
	TWh/y	p/kWh, dr 15%
Pessimistic (P10)	16.4	42.4
Base (P50)	29.0	19.7
Optimistic (P90)	38.4	14.8

Change of parameter:	Scenario	CoE increase acceptable	Tidal range decrease acceptable	Learning	Structural losses due to drag	Wake losses	Resource data (power density)	Cost data	Total Technical resource	Average CoE without learning
		%	m	%	%	%	%	%	TWh/y	p/kWh
ALL BASE	Base	20%	0.2	12%	15%	10%	100%	100%	29.0	34.7
CoE limit 10%	Worst	10%	0.2	12%	15%	10%	100%	100%	25.1	39.1
CoE limit 50%	Best	50%	0.2	12%	15%	10%	100%	100%	31.8	30.8
Tidal range 0.1	Worst	20%	0.1	12%	15%	10%	100%	100%	24.1	33.4
Tidal range 0.5	Best	20%	0.5	12%	15%	10%	100%	100%	37.5	35.2
Learning 8%	Worst	20%	0.2	8%	15%	10%	100%	100%	29.0	34.7
Learning 16%	Best	20%	0.2	16%	15%	10%	100%	100%	29.0	34.7
Structural losses 25%	Worst	20%	0.2	12%	25%	10%	100%	100%	26.7	35.4
Structural losses 5%	Best	20%	0.2	12%	5%	10%	100%	100%	31.3	34.3
Wake losses 20%	Worst	20%	0.2	12%	15%	20%	100%	100%	28.0	38.2
Wake losses 5%	Best	20%	0.2	12%	15%	5%	100%	100%	29.5	33.2
Resource data low	Worst	20%	0.2	12%	15%	10%	55%	100%	18.4	65.4
Resource data high	Best	20%	0.2	12%	15%	10%	120%	100%	30.6	32.0
Capex and Opex data high	Worst	20%	0.2	12%	15%	10%	100%	worse	28.6	43.3
Capex and Opex data low	Best	20%	0.2	12%	15%	10%	100%	best	29.0	31.2
Pessimistic (P10)	-	-	-	-	-	-	-	-	**16.4**	**74.0**
Optimistic (P90)	-	-	-	-	-	-	-	-	**38.4**	**28.3**

Table 4-3 Sensitivity analysis: all results

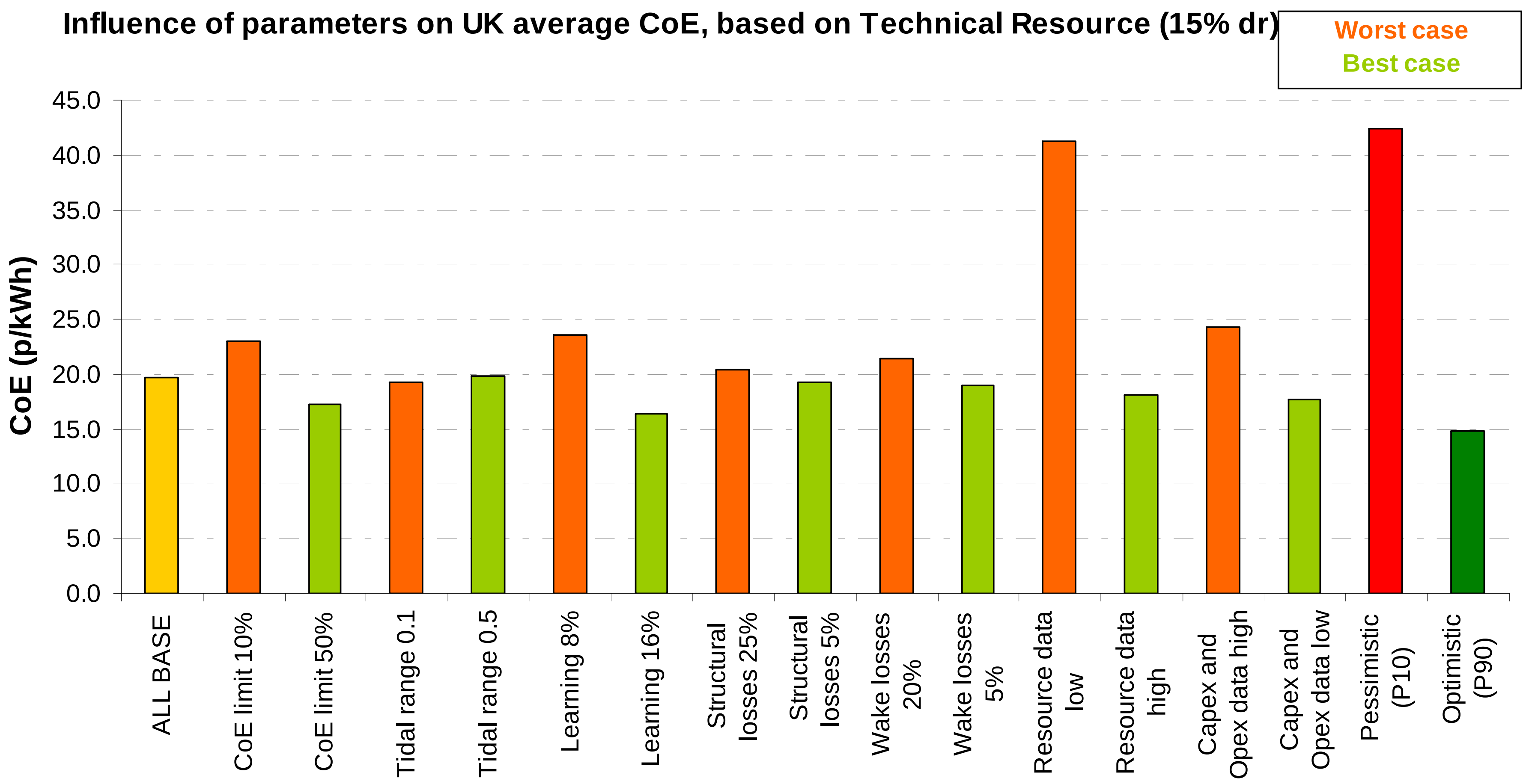

Figure 4-11 Sensitivity analysis on Cost of Energy

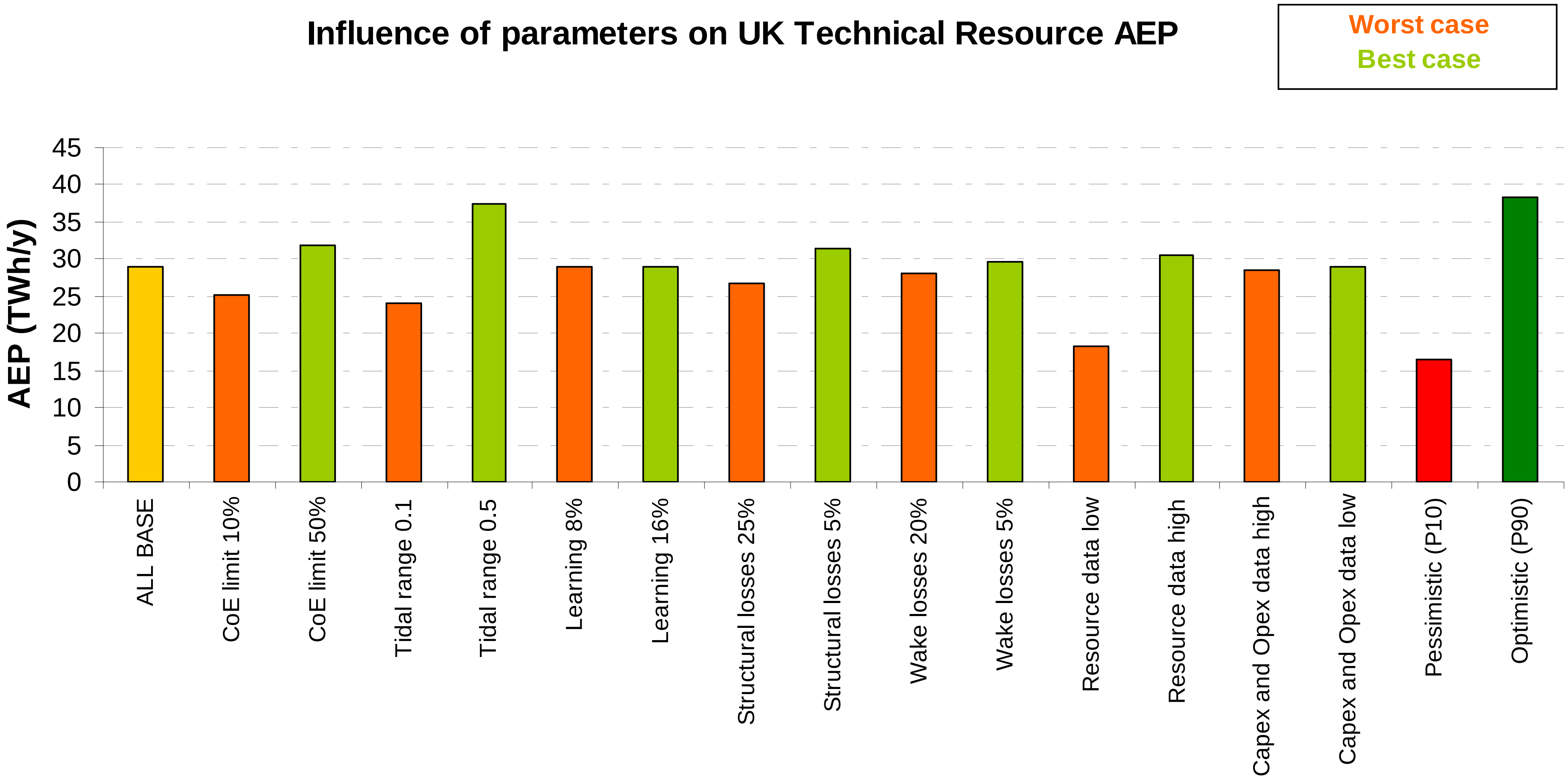

Figure 4-12 Sensitivity analysis on Annual Energy Production

4.5.2.2 Case study: tidal streaming sites

The tidal streaming sites are the least well represented by the generic analysis outlined in this report. Most UK tidal streaming sites are 'open sea' sites, as opposed to the idealised 'narrowing channel' case which has been used as the generic tidal streaming case (see Appendix C).

In all the scenarios described to this point, the energy extraction (i.e. the Flux Technical AEP) at these sites has always been limited by the prescribed tidal range change (0.1 to 0.5m as discussed earlier), based on the results from Appendix C. It is possible that energy extraction might have a lesser impact on the tidal range for open sea sites than for narrowing channel sites. On the other hand, energy extraction from open sea sites is likely to change local tidal flow patters more significantly, and reduce the tidal velocities through the farm more than would be the case for a narrowing channel, which could mean that the economics are affected to a greater degree by energy extraction than is calculated using the generic methodology. Running the Black & Veatch 2011 model with no limit on tidal range for all tidal streaming sites provides the results presented in Table 4-4. In this case, when the Flux Technical AEP limits the energy extraction for a particular site, it is by the prescribed velocity change (derived from the acceptable CoE increase).

Table 4-4 AEP and CoE results for UK resource without tidal range limit on TS sites

	Total resource	Average CoE with learning
	TWh/y	p/kWh, dr 15%
Pessimistic (P10)	19.5	42.6
Base (P50)	39.0	19.8
Optimistic (P90)	46.8	14.9

The impact on the P50 CoE figure is minimal and the CoE error bands are similar. The AEP base case estimate increases by c. 35% from 29TWh/y (see Table 4-2) to c. 39TWh/y and the overall error band on national AEP changes from c. -40% +35% to -50% +20%.

4.5.2.3 Case study: Pentland Firth sites

In Figure 4-9, the Pentland Firth (Deep and Shallow) accounts for c. 36% of the UK resource (all base case parameters). Given the potentially favourable economics of this key site (notwithstanding the challenges and costs of grid connection), it is logical to investigate allowing a greater CoE increase, enabling a higher AEP. The highest AEP is achieved when Flux Technical AEP and Farm Technical AEP are equal. Due to learning effects, the Pentland Firth can therefore be optimised in farm size and/or CoE, providing higher AEP and lower CoE for the total UK resource. Both optimisations occur at almost the same amount of energy extracted: 13.1% of the total tidal energy of the system. The absolute upper limit of energy extraction (i.e. the theoretical resource) is 20% of the total tidal energy of the system, as per Table 3-1. It should be noted that the change in velocity (18%) exceeds the arbitrarily prescribed environmental limit.

This increases the UK total AEP by c.35% from 29TWh/y (base case results shown in Table 4-2) to c. 39TWh/y (all base cases with Pentland Firth optimised for AEP and CoE). In this instance, the Pentland Firth accounts for c. 50% of the total UK resource. The UK averaged CoE decreases by c. 10% from c. 20p/kWh (base case results shown in Table 4-2) to c. 18p/kWh.

This scenario is in fact essentially the outcome of the sensitivity test which allowed the CoE to increase by 50% at step 1 of the model operation, as outlined in the general uncertainty analysis of Section 4.5.2.1: the Pentland Firth being one of the only, and by far the largest, hydraulic current site in the UK. Note that the estimated CoE for the Pentland Firth after learning has been applied remains similar to the base case, due to the additional installed capacity, as shown in Figure 4-13.

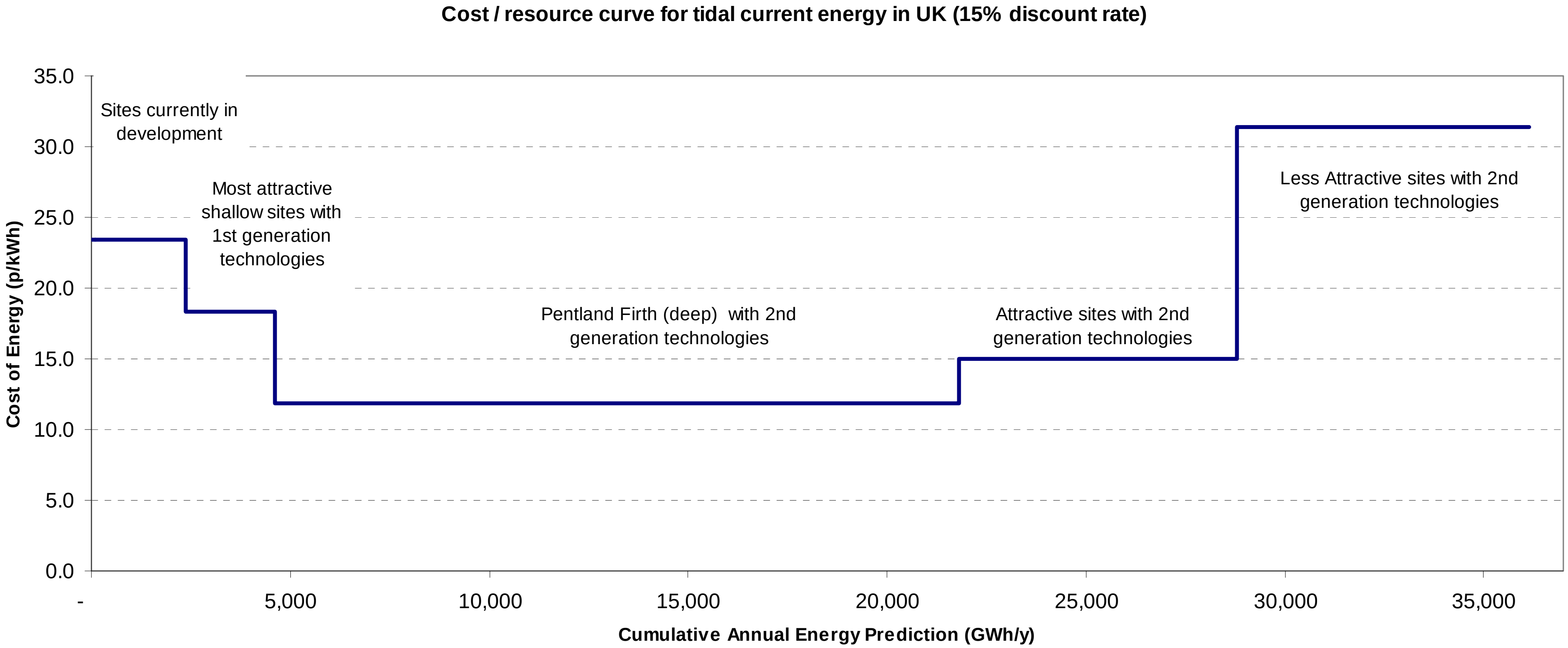

Figure 4-13 Black & Veatch 2011 model results: Cost-Resource curve with Pentland Firth optimised (P50 results only)

4.5.3 Additional resource-cost sensitivities

Black & Veatch carried out additional sensitivity analyses to better understand the influence of the economic and environmental constraints on the UK's AEP and average CoE:

1. If both constraints are switched off, in the base case P50 scenario the UK's AEP increases to c. 50TWh/y with an associated CoE of 18.9p/kWh. The UK average CoE decreases from the previous base case P50 figure (19.7p/kWh); however, the CoE for each site has actually increased as expected (as no economic limit is applied) but the resource at the most economic sites has increased more than that of the less economic sites, hence the *weighted* UK average CoE decreases. With both constraints switched off, the AEP is limited by the Farm methodology, but (importantly) with the velocities reduced according to the Flux methodology. In other words, the resource is limited by the technological approach detailed in Section 4.2.1.2 and the resultant effect of extraction on the resource. Higher rated velocities, greater overall packing densities, or changes to the assumed technology, could increase this 'technological approach resource' limit but, at least for the currently assumed technology, at the expense of significantly higher costs.
2. If only the economic constraint is applied, the UK's AEP increases to c. 39TWh/y with an associated CoE of 19.8p/kWh. The result is similar to the test case described in Section 4.5.2.2 as the tidal streaming sites are all limited by the environmental constraints in the base case.
3. If only the environmental constraint is applied, the national AEP increases to c. 36TWh/y with an associated CoE of c. 17.8p/kWh. The results are similar to the test case described in Section 4.5.2.3 as the Pentland Firth is the only site limited by the economic constraint in the base case.
4. The theoretical resource for the selected 30 sites has been calculated as per Table 3-1 and is c. 340TWh/y. However, this estimate is not particularly useful, as it cannot be extracted using the currently envisaged technological approach (as outlined in (1) above). In addition, the caveats in Section 3 regarding this approach generally providing an 'upper limit' to the theoretical resource need to be borne in mind, and at these theoretical limits for any particular site one would expect there to also be significant interactions between sites that are not accounted for in the simple summation across the different sites.

4.5.4 Comparison with the previous report

Table 4-5 shows the results of the previous Black & Veatch assessments as part of the Marine Energy Challenge (MEC) [2]. Table 4-6 summarises the output of the present 2011 study.

Table 4-5 Summary of MEC Phase I and Phase II Technical Resource for key sites

Ranking	Site Name	Phase I (GWh/y)	Phase II (GWh/y)
1	Pentland Skerries	3901	4526
2	Stroma P. Firth	2774	2114 (eliminated)
3	Duncansby Head	2031	1699
4	Casquets	1651	418
5	S. Ronaldsay P. Firth	1518	1030
6	Hoy, Pentland Firth	1377	714
7	Race of Alderney	1365	365
8	S. Ronaldsay/ P.Skerries	1147	964 (eliminated)
9	Rathlin Island	866	408
10	Mull of Galloway	806	383
	Total top 10 sites	**17,436**	
	Total UK sites	**21,812**	**18,000 +/- 30%**

Table 4-6 Summary of Black & Veatch 2011 assessment (P50 values)

Ranking	Site Name	AEP (GWh/y)
1	Pentland Firth Deep	10,067
2	Race of Alderney	2,253
3	Carmel Head	1,948
4	South Jersey	1,904
5	East Casquets	1,891
6	Pentland Firth Shallow	1,230
7	North East Jersey	1,165
8	West Islay	1,164
9	Islay / Mull of OA	869
10	Ramsey Island	807
	Total top 10 sites	**23,297**
	Total UK sites	**29,020 (-45%/+30%**

The updated methodology gives a revised base case estimate c. 60% higher than the 2005 Black & Veatch Phase 2 estimate (which was estimated to have an overall P10/P90 error band of +/-30%). The error band using the updated methodology is +30%/-45% using statistical analysis of a number of scenarios, as outlined in Table 4-3 and Figure 4-12. There remains high uncertainty in the resource associated with tidal streaming sites. The Pentland Firth base case AEP has increased by 40% from c. 8TWh/y in the Black & Veatch Phase 2 report to c. 11TWh/y in this analysis.

5 CONSIDERATION OF OTHER KEY CONSTRAINTS

5.1 Methodology

With assistance from the Crown Estate and its MaRS GIS model, Black & Veatch identified the other key constraints (excluding grid connection constraints) for each of the 30 sites. More than 100 constraints were initially investigated. The relevant constraints were treated either as exclusion zones, as shown in Table 5-1, or as restricted zones, as shown in Table 5-2. Weightings were applied to the different constraints in the restriction zones.

Table 5-1 Exclusion zones used in the Black & Veatch 2011 model (from the Crown Estate's MaRS model)

Exclusion Zones	
Feature	Buffer (m)
Round 1 Wind Farm Lease	
Round 2 Wind Farm Lease	
Round 3 Wind Farm Zone	
Scottish Wind Farm Exclusivity Awards	
Round 1 wind Farm Exclusion Zone	
Round 1 & 2 Wind Farm Extension Sites	
Wind Farm Demonstration Sites	
Blyth Wind Farm	
Active Cables	250
Inactive Cables	50
Active Pipelines	500
Inactive Pipelines	50
Wells (active and inactive)	500
Subsurface Infrastructure	500
Surface Infrastructure	250
Oil and Gas Safety Zones	
Anemometers	500
Protected Wrecks	100
Current Aquaculture Leases	
Pending Aquaculture Leases	
Fisheries	
Gas Storage Leases	
Dredging Prospecting	
Dredging Options	
Dredging Licences	
Dredging Applications	
IMO Route	3704
Munitions Dumps	
Disposal Sites - Open	
Anchorage Areas	
Navigation Points	100
Ramsar Sites	
World Heritage Sites	

Table 5-2 Restriction zones used in the Black & Veatch 2011 model (from the Crown Estate's MaRS model)

Restriction Zones
Input Feature
Shipping Density
Total Annual Fishing Value
Merged layer of SSSIs, SPAs (incl. pSPA, cSPA), SACs (Incl. dSAC, pSAC, cSAC) and SAMs
Merged layer of AONBs, NNRs, LNRs
MNR
Unprotected Wrecks
Unprotected Wrecks (Polygons)
Disposal Sites - Disused or Closed
Dredging Prospecting - 2km Buffer
Dredging Options - 2km Buffer
Dredging Licences - 2km Buffer
Dredging Applications - 2km Buffer

After analysing the influence of the selected restriction zones on the various sites and the UK's AEP, only three constraints potentially impede development of commercial tidal stream arrays: fishing, shipping and designated conservation sites[5].

The assumed probability of a site gaining the relevant consents and thus potentially being fully developed (or the proportion of the site being developed) has been assessed[6] based on experience of existing offshore wind and marine energy projects, and is presented in Table 5-3, Table 5-4 and Table 5-5.

Table 5-3 Shipping numbers (per cell[7]) and probability of site being developed

Ships per day	Ships per year	Low constraint	Base constraint	High constraint
0	0	100%	100%	100%
1	365	90%	85%	80%
2	730	80%	70%	60%
3	1095	70%	55%	40%
4	1460	60%	40%	20%
5	1825	50%	25%	0%
6	2190	40%	10%	0%
7	2555	30%	0%	0%
8	2920	20%	0%	0%
9	3285	10%	0%	0%
10	3650	0%	0%	0%

[5] 'Designated conservation sites' comprise those areas protected under UK and/ or European Law for the purposes of nature, cultural heritage or landscape conservation. In the case of European protected sites these also include draft, proposed or candidate sites. The details are provided in Table 5-2.
[6] This assessment was undertaken with input from Entec, Carbon Trust.
[7] Shipping data cell size = 2 x 2 nautical miles.

Table 5-4 Designated conservation sites and probability of site being developed

Designated conservation site coverage	Low constraint	Base constraint	High constraint
0%	100%	100%	100%
100%[8]	90%	50%	10%

Table 5-5 Fishing value and probability of site being developed

Fishing £k/year/cell[9]	Low constraint	Base constraint	High constraint
0	100%	100%	100%
10	100%	97%	93%
20	100%	93%	87%
30	100%	90%	80%
40	100%	87%	73%
50	100%	83%	67%
60	100%	80%	60%
70	100%	77%	53%
80	100%	73%	47%
90	100%	70%	40%
100	100%	67%	33%
110	100%	63%	27%
120	100%	60%	20%
130	100%	57%	13%
140	100%	53%	7%
150	100%	50%	0%
160	100%	47%	0%
170	100%	43%	0%
180	100%	40%	0%
190	100%	37%	0%
200	100%	33%	0%
210	100%	30%	0%
220	100%	27%	0%
230	100%	23%	0%
240	100%	20%	0%
250	100%	17%	0%
260	100%	13%	0%
270	100%	10%	0%
280	100%	7%	0%
290	100%	3%	0%
300	100%	0%	0%

[8] Potential tidal current sites that overlap with designated conservation sites generally have 100% coverage.
[9] Fishing data cell size = 1 ICES rectangle (around 5 x 5km).

The overall probability of a site being developed (or partly developed) is the product of the above three probabilities for each site (Fishing x Shipping x Designated conservation sites). The results are presented in Table 5-6.

Table 5-6 Constraints analysis: methodology and results[10]

Sites	Technical AEP Base case P50	Shipping (ships/yr/cell)	Fishing (£/yr/cell)	National Design.	Shipping			Fishing			Nat Desig			Site probability low	Site probability base	Site probability high	Practical AEP (GWh/yr)		
	GWh/y	1.000	1.000	1.000	Low	Base	High	Low	Base	High	Low	Base	High		%		Low	Base	High
Kyle Rhea	102	-	1,100	100%	100%	100%	100%	100%	100%	99%	90%	50%	10%	90%	50%	10%	92	51	10
Strangford Lough	281	-	-	100%	100%	100%	100%	100%	100%	100%	90%	50%	10%	90%	50%	10%	253	140	28
Pentland Firth Shallow	1,230	-	-	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	1,230	1,230	1,230
Westray Firth	750	-	17,100	0%	100%	100%	100%	100%	94%	89%	100%	100%	100%	100%	94%	89%	750	706	666
Race of Alderney	2,253	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	90%	71%	54%	2,024	1,595	1,210
Pentland Firth Deep	10,067	750	25,800	0%	100%	70%	50%	100%	91%	83%	100%	100%	100%	100%	64%	41%	10,067	6,431	4,175
Blue Mull Sound	60	-	12,000	0%	100%	100%	100%	100%	96%	92%	100%	100%	100%	100%	96%	92%	60	58	55
Mull of Kintyre	444	356	42,800	0%	90%	85%	80%	100%	86%	71%	100%	100%	100%	90%	73%	57%	401	326	255
Islay / Mull of OA	869	77	11,500	0%	98%	97%	96%	100%	96%	92%	100%	100%	100%	98%	93%	88%	850	811	766
Rathlin Island	172	2	11,200	0%	100%	100%	100%	100%	97%	92%	100%	100%	100%	100%	96%	92%	172	166	158
Ramsey Island	807	237	8,700	100%	94%	90%	87%	100%	97%	94%	90%	50%	10%	84%	44%	8%	679	355	66
East Rathlin Sound	95	-	5,000	0%	100%	100%	100%	100%	99%	97%	100%	100%	100%	100%	99%	97%	95	94	92
Firth	409	-	14,800	0%	100%	100%	100%	100%	95%	90%	100%	100%	100%	100%	95%	90%	409	389	369
Carmel Head 1+3	1,461	6	20,000	0%	100%	100%	100%	100%	93%	87%	100%	100%	100%	100%	93%	87%	1,459	1,356	1,267
Carmel Head 2	487	1,640	19,500	0%	55%	33%	10%	100%	93%	87%	100%	100%	100%	55%	30%	9%	268	148	43
West Islay	1,164	152	12,800	0%	96%	94%	92%	100%	96%	91%	100%	100%	100%	96%	90%	84%	1,116	1,046	974
Big Russel	41	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	90%	71%	54%	37	29	22
Channel	66	-	11,200	0%	100%	100%	100%	100%	97%	92%	100%	100%	100%	100%	97%	92%	66	64	61
Bristol Channel - Minehead	633	763	1,200	0%	79%	69%	58%	100%	100%	99%	100%	100%	100%	79%	68%	58%	501	433	365
Bristol Channel - Mackenzie shoal	273	972	1,276	100%	73%	60%	47%	100%	100%	99%	90%	50%	10%	66%	30%	5%	180	82	13
West Casquets	522	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	90%	71%	54%	469	370	281
Isle of Wight	490	668	48,300	0%	82%	73%	63%	100%	84%	68%	100%	100%	100%	82%	61%	43%	400	297	211
East Casquets	1,891	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	90%	71%	54%	1,699	1,339	1,016
Mull of Galloway	306	297	5,900	0%	92%	88%	84%	100%	98%	96%	100%	100%	100%	92%	86%	80%	281	264	246
Uwchmynydd	34	-	4,400	100%	100%	100%	100%	100%	99%	97%	90%	50%	10%	90%	49%	10%	31	17	3
Barry Bristol Channel	306	1,260	1,270	0%	65%	48%	31%	100%	100%	99%	100%	100%	100%	65%	48%	31%	201	147	94
Portland Bill	44	56	27,500	100%	98%	98%	97%	100%	91%	82%	90%	50%	10%	89%	44%	8%	39	19	3
N. Ronaldsay Firth	399	-	13,900	100%	100%	100%	100%	100%	95%	91%	90%	50%	10%	90%	48%	9%	359	191	36
North East Jersey	1,165	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	90%	71%	54%	1,046	825	626
South Jersey	1,904	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	90%	71%	54%	1,710	1,348	1,023
South Minquiers (Jersey)	294	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	90%	71%	54%	264	208	158
TOTAL	29,020																**27,207**	**20,532**	**15,522**

10 Grey cells are the cells where no data was available from the MaRS model, and blue cells represent some 'special case' sites (as described further below).

Some sites were treated as special cases. These are highlighted in light blue and grey in Table 5-6:

1. Channel Islands: No data was available to Black & Veatch at the time the study was completed. Average UK figures have therefore been applied to the Channel Islands results.
2. Carmel Head: This site has three areas of high resource (geographically separated but physically on the same flux line). Area 2 features a high shipping density as it lies on busy ferry lanes, which is not the case for Areas 1 and 3.
3. Pentland Firth: Unlike all the other sites, the Pentland Firth is too large to consider the shipping constraint across the entire site. It has been assumed that, under a significant development scenario, shipping lanes would be created which would cover c. 20% of the area identified as potentially suitable for commercial tidal stream development. Customised probabilities for the shipping constraint have therefore been developed, noting that in the earlier base case P50 scenario only c. 30% of the Pentland Firth area is utilised by the development (as this site is economically constrained through the flux method). The Pentland Firth (shallow) site partly lies within a designated conservation site zone (around Stroma). However, after the recent announcements concerning the MeyGen development, a 100% probability has been applied to this site with respect to designated conservation sites.

5.2 Results

Table 5-6 suggests that in the base case c. 70% of the technical resource is retained after these key practical constraints (excluding grid connection) are applied, and the UK's practical AEP is c. 20TWh/y (ranging from 16TWh/y to 27TWh/y for the pessimistic and optimistic cases, assuming the same underlying base case technical resource). Approximately half of the variance between the base case and the optimistic and pessimistic cases is due solely to the uncertainty in the Pentland Firth (deep) site which is largely driven by the shipping assumptions discussed above. The associated UK averaged CoE increases to c. 21p/kWh.

The uncertainty around the constraints has been incorporated into the previous uncertainty analysis, and hence the overall uncertainty of the practical resource is slightly higher than for the technical resource: c. -50%/+45% for the AEP and c. -25%/+115% for the CoE, as shown in Table 5-7.

Table 5-7 Results for practical resource (AEP and CoE, dr 15%)

	Total Practical resource	**Average CoE with learning**
	TWh/y	p/kWh
Pessimistic (P10)	10.3	45.2
Base (P50)	20.6	21.0
Optimistic (P90)	30.0	15.5

5.3 Additional discussion

The two main limitations of the Black & Veatch 2011 model are discussed below:

- This work is not intended to provide reliable results for any specific site. The entire project was conducted to estimate a UK technical and practical resource and associated economic estimates. This is only possible using the many assumptions discussed throughout the report. In order to accurately estimate the response of a site specific tidal system due to energy extraction, we recommend the direct incorporation of the proposed energy extraction into a refined hydrodynamic model (which has been undertaken for a number of sites globally, but this technique was not possible within the budget constraints of this work, and in any case there would have been significant remaining uncertainties in the acceptable limits for the various impacts).

- Grid accessibility (i.e. connection constraint) has not been considered as part of this study.

6 SUGGESTIONS FOR FURTHER WORK

An issue requiring further consideration is the prescription of how much of the energy removal from the tidal hydrodynamic system can actually be ascribed to useful energy generation. The energy removal from the system that is due simply to the presence of the TEC device itself has not been considered in detail in the analysis presented in this report. Future focus to reduce this wasteful use of the resource by improved support structure design and streamlining has the potential to significantly reduce this loss of useful energy that would otherwise be available for harvesting. Prescription of wake losses in large tidal current farms is another area that requires further research. The offshore wind industry has shown the importance of this field [19] and tidal specific research of wake propagation has been undertaken [16, 17], and is a major focus on the PerAWaT project being run by the Energy Technologies Institute.

It has been shown that one of the most significant sources of uncertainty in the results remains the actual underlying resource data used to conduct this analysis. Comparison between MEA and tidal diamond figures showed significant discrepancies which led to the large error bands used on the final UK resource estimate (and economics). Further work to understand these discrepancies, and undertaking ADCP measurements (or public domain collation of previous measurements) at various sites, would be extremely beneficial in terms of mitigating this uncertainty.

The assessment of grid accessibility (and the real cost of connection on a site by site basis) is a key potential constraint on UK's practical resource. This should be investigated further, to assist with prioritising key sites for future development.

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APPENDIX A: UK MAPS –RESOURCE & COE (WITH AND WITHOUT LEARNING)

These are available separately from the Carbon Trust at:

http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/marine-energy-accelerator/pages/default.aspx

APPENDIX B: UK SITE MAPS

These are available separately from the Carbon Trust at:

http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/marine-energy-accelerator/pages/default.aspx

APPENDIX C

This is available separately from the Carbon Trust at:

http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/marine-energy-accelerator/pages/default.aspx