1. Introduction

1.1 Overview

This report provides a technical description of the Atlas of UK Marine Renewable Energy Resources. It supersedes all previous reports and describes the data sources, methods of analysis, structure of the interrogative database and finally provides an overview of the resource maps provided and the use of the database to assist future decisions on strategic areas for marine renewables.

Chapter 1: provides an introduction to the project, including the study rationale and study area.

Chapter 2: describes the source information used in the derivation of the tidal, wave and wind resources.

Chapter 3: lists the parameters used to describe the wind, wave and tidal energy resources. In addition, specific equations used to calculate the power variable for each resource are provided.

Chapter 4: details the process undertaken to derive a consistent mapping framework for the resource data. In addition, an overview of the maps included in the Atlas is provided.

Chapter 5: provides an outline description of the validation of the data used in the Atlas.

Chapter 6: describes the spatial database developed within the GIS system.

Chapter 7: suggests recommendations to maintain the Atlas as the state-of-the-art database of marine renewable resources.

1.2 Study Rationale

There is a growing expectation that the energy resources created by the dynamics of the marine environment will be able to make a real and measurable contribution to the Renewables Agenda over the next 10 years, both nationally and globally. However, what is presently unavailable is any detailed quantification of this resource (waves, tides and offshore winds) across the waters of the UK Continental Shelf (UKCS).

Before the UK can forge ahead with any large-scale deployments of energy converters in the marine environment it has an obligation to conduct a Strategic Environmental Assessment (SEA) of the issues relevant to such a development. This work has already commenced and a Phase 1 SEA has been completed (BMT, 2003) for offshore wind[1] in three priority areas (referred to as Thames Estuary, Greater Wash and Liverpool Bay), but as yet is not supported by any resource quantification (neither winds, waves or tides). It is therefore relevant that a study is undertaken to survey the potential marine energy resource over the scale of the SEA area, i.e. the UKCS, to inform the planning process and assist in future site selection.

The aim of the present study is therefore to provide an Atlas of the UK Marine Renewable Energy Resources (hereafter called 'the Atlas') to describe a spatial quantification of waves, tides and offshore winds at a regional scale over the area of the UKCS. The approach taken to deliver this work has been to identify and review the range of work already undertaken, and provide a more detailed and consistent description of the marine resource by making use of the best available data and technical expertise.

To ensure the information provided to the Atlas is managed and maintained most effectively, all the derived marine resource parameters have been captured in a structured database, within a Geographical Information System (GIS), so enabling data presentation and interrogation.

1.3 Study Area

The study area includes the marine waters extending across the entire UKCS, including the territorial sea around the Channel Islands, as shown in Figure 1. At the time of this report, there is currently no legislation to support the installation of marine technologies outside the territorial sea (12 nautical mile) limit. The proposed development of the Renewable Energy Zone (REZ) will allow the exploitation of renewable marine resources out to the 200 nautical mile limit. Thus the coverage provided by the Atlas will enable informed decisions to be made for the entirety of the REZ. Within the study area, the marine renewable energy resource has been quantified and described at a regional scale according to a number of principal components:

- Tidal Resource
  The tidal resource is identified by the spatial variation in amplitudes of water levels and currents, with the currents being further sub-divided into thirty-four layers through the water column.

1 Referred to as Round 2 Offshore Windfarms

- Wave Resource
  The wave resource is determined from the amplitude of wave heights and wave period propagating across the sea surface.

- Offshore Wind Resource
  The offshore wind resource is derived from wind speed values taken at a consistent height above the sea surface related to present hub heights being designed for offshore wind farm installations.

2. Information Sources

The rationale for the Atlas design has been to compile sets of marine resource information that provide complete and consistent data coverage over the extent of the study area. The main data providers to the project are the Met Office and Proudman Oceanographic Laboratory (POL) who each operate regional scale models which, in combination, provide the required definitions of offshore wind, wave and tidal parameters. Other base mapping details have been sourced from the (US) Defence Mapping Agency and the (US) Naval Oceanographic Office.

Initial tidal parameters were based on the POL Continental Shelf model (CS3). During the timeframe of the project, POL completed the development of a fine detail UK Waters model which calculates tidal parameters at a 1 nautical mile (approximately 1.8km) resolution. This High Resolution Continental Shelf (HRCS) model has 367,395 grid points of which 175,000 fall within the study area. This model represents the state-of-the-art in tidal modelling (it was run on 64 processors of POL's Cluster Computer) and the Atlas project is the first to publish the outputs. Such information provides significant improvements in tidal stream detail around nearshore locations, headlands and narrow tidal straits. This is of particular importance when considering the tidal regime as it is more spatially confined, unlike the wave and wind resources which tend to be more spatially consistent.

Wind and wave resource information are both sourced from the same model suite operated by the Met Office. The UK Waters Wave model presently offers the best source of detailed wave information around UK waters. This model came into operation in June 2000. At the stage of data extraction from the model archive a total of 3 years and 3 months (inclusive) was available (June 2000 to September 2003). This model was used in preference to the European Wave Model, which contains a longer data archive, as there was a need to balance the longest available time-series of wave data with the high spatial resolution needed to best resolve geographical variations in wave resource over the UKCS.

The work presented is therefore based on the best available data at the time of publication.

The following limitations are acknowledged in the present mapping and relate mostly to the nearshore and shallow water coastal areas:

- Wave Resource
  The transformation of deepwater offshore waves towards shallower, nearshore areas is not robustly represented in the present numerical scheme. In addition, the numerical model is based upon 3 years and 3 months of archived data, however the validity of using this has been tested through the comparison of other, longer, databases;

- Wind Resource
  The modelling of nearshore winds does not robustly address coastal effects, in particular those locations where the bathymetry influences the wave form. Adjustments have been made through the use of a coastal adjustment model and presented as a separate layer in the Atlas. In addition, the numerical model is based upon 3 years and 3 months of archived data, however the validity of using this has been tested through the comparison of other, longer, databases;

- General
  - The Atlas does not consider the resource available within estuaries; and
  - Calculations of energy yield do not consider the effects of downstream losses as a consequence of the installation of a technology.

As stated, the Atlas provides resource information on a regional scale over the extent of the UKCS and is suited to strategic level considerations. If a specific area is taken forward for development, then site specific measurements will be required.

2.1 Bathymetry

Bathymetric information has been obtained from two main sources, which together provide coverage of the entire UKCS.

The first dataset is from the (US) Naval Oceanographic Office. It is a single consistent dataset quoted to a standard datum and projection. The dataset made use of in the Atlas predominately covers those areas of the UKCS which are deeper than 200m water depth.

The second dataset was sourced from POL's HRCS model (see Section 2.3) which was constructed from a variety of sources. This dataset covers all locations shallower than 200m water depth. The underlying bathymetry originates from the GEBCO (General Bathymetric Chart of the Oceans) 1 minute digitised bathymetry. This data source is state-of-the-art, having been produced through an initiative to assist the numerical modelling of surges studies in the North Sea (see Appendix A1). This data set was interpolated onto the model grid and the coastline guided (but not defined) by the World Vector Shoreline. Where possible, the bathymetry has been improved by the replacement of the GEBCO depths with bathymetry from higher resolution datasets available to POL. This has provided significant improvements over GEBCO bathymetry in near-shore inter-tidal regions.

The coastline used in the Atlas is sourced from the DEAL Data Registry. Both the coastline and US Naval Oceanographic Office bathymetric data are fully in the public domain.

Figure 1 illustrates the bathymetry across the UKCS using a variable depth scale that classes values to allow visualisation across shallow nearshore zones (<5 to 50m depth), intermediate depths (50 to 500m), and deep water locations (500 to 5000m).

2.2 Electricity Grid

Details of the high voltage (HV) electricity grid network covering England, Wales and Scotland have been obtained from the former Electricity Association and validated against separate details provide from National Grid Transco. It is noted here that the capacity of the HV grid is not described in this data in any way, and that the distribution circuits operating at 132kV and below are also not presented.

2.3 Tidal Data

The primary source for tidal data is from the POL CS3 and HRCS models. However, for outer shelf locations the coarser North-East Atlantic (NEA) Model has been used to complete the description of tidal energy resource out to the extent of the UKCS (Figure 2).

In further detail :

- NEA
  This model is based on a grid with a resolution of 1/3° latitude by 1/2° longitude (approximately 35km). The model is two-dimensional (2Dh) providing depth-averaged parameters;

- CS3
  This model operates on a grid with a resolution of 1/9° latitude by 1/6° longitude (around 12km). This model is also 2Dh providing depth-averaged parameters. The CS3 and NEA are operational models that are linked together, with boundary conditions taken from NEA to drive CS3; and

- HRCS
  This model is applied using a detailed grid with a refined resolution of 1/60° latitude x 1/40° longitude (1 nautical mile (approximately 1.8km)). This model

provides the highest resolution of tidal data available to date covering those depths less than 200m within the UKCS. It is three-dimensional (3Dh), providing thirty-four levels through the vertical. The HRCS takes its boundary conditions from the Atlantic Margin Model (AMM). The model configuration is described further in Appendix B1.

Information for the Atlas has been developed from a prediction of a complete representative annual tidal event (and assuming that year to year variations are insignificant). These predictions are based on operating the models with 30 tidal harmonics to generate standard outputs of water level, current speed and current direction.

2.4 Wave Data

The main source of wave information has been made available from the Met Office and is developed from the UK Waters Wave Model (spatial resolution 12km) and Global Wave Model (spatial resolution 60km) (Table 1). These models maintain a realistic simulation of wave conditions shelf-wide by being run on a regular basis (four times daily for UK Waters, twice daily for the Global model) forced by wind data from an atmospheric model which includes assimilation of observations of actual weather conditions.

Table 1. Data used to describe the wave resource

Model	Spatial Resolution	Period
UK Wave	12km	1 June 2000 to 30 September 2003
Global Wave	60km	1 June 2000 to 30 September 2003

The wave models are based on a 2nd generation spectral scheme (Golding, 1983) which can typically resolve waves with periods between 3 and 25 seconds, and deep-water wavelengths from 15 to 975m. The models are forced using the wind field 10m above mean sea-level derived by the Met Office atmospheric models, which assimilate observational data from satellite, ship and met buoy networks. It is the wind strength, duration and direction that defines the frequency and directional bins in which energy is transferred to the wave model through the process of 'wind-sea' growth. Parameterisations of the wind-sea spectral peaked-ness and peak frequency are used to select an appropriate member of the JONSWAP family of spectra to represent the growing wind-sea.

Wave energy falling outside of the wind-sea frequency and direction range is treated as swell, and advected through the model domain. Further physical changes to the wave field can occur through energy dissipation from bottom friction and wave breaking, or energy redistribution through the frequency band due to non-linear inter-frequency interactions. All are treated through parameterisations which modify the appropriate bins of the wave model spectrum. In shallow water, the wave group speed depth dependency and refraction are represented in the model physics.

The UK Waters Wave Model additionally includes the effects of time-varying currents. The wave model output has previously been verified using the available network of Marine Automatic Weather Station (MAWS) wave buoys to provide information on wave height and period which is compared directly with model output.

The UK Waters Wave Model provides coverage over the major part of the UKCS, with the exception of outer shelf areas and has a resolution of 1/9° latitude by 1/6° longitude (approximately 11km in mid-latitudes). It is useful to note at this point that there is general alignment between this model and the POL CS3 model and each providing the same grid cell dimensions. The UK Waters Wave Model became operational in June 2000 and has an archive of results stored at hourly intervals from the last 3 years and 3 months, approximately.

Areas outside of the UK Waters Wave Model are described by the Global Wave Model which provides a resolution of 5/9° latitude by 5/6° longitude (approximately 60km square grid at mid-latitudes). Figure 3 presents the layout of grid cells adopted by the Atlas from these two wave models.

Since year to year variations may occur in wave data, it has been necessary to sample from the entire archive of the UK Waters Wave Model to produce a 'synoptic' description of representative wave parameters. Matching data over this period has been added from the Global Wave Model for outer shelf locations. Standard model output developed from the archives includes resultant significant wave height, zero up-crossing period and wave direction.

2.5 Offshore Wind Data

The primary source of the raw data for the wind resource has been made available from the Met Office Numerical Weather Prediction (NWP) system, a description of which is provided in Appendix C1.

Operationally, the Met Office runs two configurations of this model :

- The NWP global model has a resolution of 5/9° latitude by 5/6° longitude (approximately 60km in mid-latitudes). There are 30 vertical levels with humidity calculated on the lowest 27 levels; and

- The NWP mesoscale model, which is a regional model centred on the United Kingdom. This has a resolution of 1/9° latitude by 1/6° longitude (approximately 11km in mid-latitudes). It has 38 vertical levels with additional levels in the boundary layer to provide extra detail for forecasting over the UK.

Forecasts for the global model are updated 6 times per day, and for the mesoscale model four times per day. Until September 2000, the data used was from pressure level 1, which, although variable, approximates to 19.5m ASL (Above Sea Level; assuming neutral atmospheric stability). In 2000, the NWP model was changed to produce wind data at constant 10m asl height. Therefore, in order to preserve archive consistency, the data from the NWP from 2000 onwards was scaled back to 19.5m. The scaling equation used is: (wind speed at 10m) = 0.94 * (wind speed at 19.5m) All data supplied to the Atlas from the Met Office has been provided at 19.5m height above sea level.

The wind data calculated by this model is then used as boundary conditions into the Met Office wave models, such that the wind data used within the Atlas originates from (Figure 4):

- The UK Waters Wave Model is being used for the nearshore areas. It provides data over a shorter period of time than the global model, but it has a higher resolution, which is essential in giving more detail and is believed to be more accurate for the UK waters. Because of changes mentioned earlier, the global model is in any case consistent over the long term;

- The Global Wave Model is being used for the outer western and northern extremes of the UK Continental Shelf (UKCS) not covered by the UK Waters Wave model. For consistency, duration of data provided is the same as that available from the UK Waters Wave model; and

In addition, a set of representative data points from the European wave model is being used for the extraction of long-term (approximately 13 years) data for comparison. The data used to describe the wind resource is summarised in Table 2.

Table 2. Data used to describe the wind resource

Data Specification	Period	Model
3 hourly wind speed and direction time histories for each grid point.	1 June 2000 to 30 September 2003	UK and Global Wave
3 hourly wind speed and direction time histories for 21 representative points (see Appendix C4; Figure C4.3).	12 June 1991 to 1 March 2004	European Wave

Whilst the Met Office models provide the best available information for the UKCS, the predications for the shallow nearshore areas are not robustly described (see Section 2). Therefore, to provide further wind information for this coastal zone (here described as being less than 30km from the coast) an additional modelling approach has been adopted. The computational wind flow model WAsP (Troen and Petersen, 1989) has been used and approaches adopted from previous work, most notably the POWER study (Halliday *et al*., 2001). Whilst this work provides a useful comparison in the nearshore zone, the requirement of the Atlas to provide a regional assessment of the marine resources are such that the details on this approach are described in Appendix C2.

The final dataset held within the Atlas therefore comprises data from three different sources and thus three different resolutions :

- 5km for data within 30km from the coast (WAsP model);
- 12km for data from the UK Waters Model; and
- 60km for data from the Global model.

3. Related Studies

Prior to the Atlas project it is recognised that there have been several earlier studies which have each attempted to quantify aspects of the offshore marine resource for areas around the UK. In most cases, the interest of these previous studies has been discrete in their geographic focus and towards either offshore wind, wave or tidal resources. One example is DTI (1991) which provided a limited set of resource calculations at discrete locations around the UK with data sourced from selected sites from the European Wave Model (see also Section 5.3.2). Such studies are listed in the reference section, with two of the most recent activities described below.

The approach taken in the generation of the Atlas has been to recognise the value from these previous studies and to provide an improved level of understanding and integration of information, but also in a structure that can be further refined in due course as better information comes available.

3.1 Seapower South West

The South West Regional Development Agency (SWRDA) has recently conducted an initiative called Seapower South West. This project has a geographic focus on the South West of England, extending from the North Devon coast in the Bristol Channel and around to Portland Bill in the English Channel. To date an Initial Review has been completed to identify and map coastal grid connections, planning constraints including fisheries, habitats, shipping and exclusion zones, consolidate existing information on physical resource (wave and tidal flow only) and bathymetry and report outlining the maximum credible and most likely scenarios for MW installed and GWh/year contributions to 2010 and 2020 targets (SWRDA, 2003).

The initial review for the Seapower South West project was identified by the Atlas project prior to the commission in October 2003 and DTI advised on the content and scope. Since this date, ABPmer maintained close liaison with the contractor who undertook this work to ensure maximum benefits could be achieved between both projects.

Primary marine data sources for the Seapower South West project are the Met Office wave models and a UK Shelf Model operated by Plymouth Marine Laboratory (PML) for tidal data. The Met Office models used were the European and UK Waters Models from which seven data points from the former and four points from the latter were used to derive the wave characteristics for sites off the north facing coast only. The tidal model used in the Seapower study is comparable to the CS3 operated by POL, but has a more refined grid offering a 5km resolution. PML has operated their model to describe a 15 day spring-neap tidal cycle, and used this data to describe tidal current speed and direction for the south west region of the UK, and also for the UK and North Sea as context for the resource in the south west region (Metoc, 2004).

It is noted that the POL HRCS model provides the best available resource of high resolution data across the UKCS allowing improved definition at locations of particular interest, such as headlands and tidal straits.

3.2 Marine Energy Challenge, Carbon Trust

The Carbon Trust is presently responsible for an initiative known as the Marine Energy Challenge. This programme has the aim to 'assess the potential for marine energy devices to achieve a competitive cost of electricity generation against other renewables and fossil fuelled power generation' (Carbon Trust, 2004). Part of this project is to assess the state of wave and tidal marine technologies and is working with eight technology developers to reach this. The Atlas project team has been in liaison with the Marine Energy Challenge to help improve the current understanding of technologies held within the Atlas database. For further information related to this see http://www.thecarbontrust.co.uk/carbontrust/low_carbon_tech/dlct2_3_1.html.

4. Derivation of Marine Resource Parameters

A set of principal marine resource parameters have been derived for the Atlas to quantify the envelope of spatial and appropriate temporal variations.

4.1 Tidal Resource

The main tidal resource parameters included in the Atlas are :

- tidal range;
- tidal flows; and
- annual tidal power estimates

Values are derived from a complete year of tidal cycles. Calculations have been based either on ellipse properties of the four major (two diurnal and two semi-diurnal) tidal harmonics, or the instantaneous values derived from thirty (CS3) and fifteen (HRCS) tidal constituents during a representative period.

The temporal scales used to describe the inter-annual variation in the tidal resource are therefore :

- spring tidal cycle; and
- neap tidal cycle.

The tides are a regular and predictable phenomenon caused by the gravitational attraction of the moon and sun acting on the oceans of the rotating earth. Most locations around the UK are semi-diurnal, experiencing two high and two low waters each day (the average interval between successive high waters is approximately 12 hours 25 minutes.

The relative motions of the earth, moon and sun cause the tides to vary with various other regular cycles, of which the two most important ones are :

- the fortnightly cycle (or 14.77 days). This results from the tidal influence of the sun and moon either reinforcing each other (called spring tides) or partially cancelling each other (neap tides). This is called the spring-neap cycle; and

- a half yearly cycle caused by the tilt of the earth, and its orbit around the Sun which leads to higher than average spring tides around the time of the equinoxes (March and September) and lower than average spring tides in June and December.

On average, the spring tidal currents are around double those of the neap tides. In terms of raw power available, spring tidal currents can generate around eight times the power of neaps. The spring tides usually occur 1 to 2 days after full and new moon, with neap tides experienced just after the first and third quarter of the new moon. A table of full moons is given in Appendix B2.

In addition to a horizontal spatial description of the tidal resource across the UKCS, tidal flows will vary through depth. A further spatial scale is therefore provided through depth with quantification offered for depths from 100% to 0% above the bed in 10% increments.

For those few areas where data remains from the CS3 model, it should be noted that the original depth-averaged values have been corrected to provide surface predictions. This ensures that all of the data is consistent. These have been converted using the scaling values provided in Appendix B3 (Table B3.1; Figure B3.1). In a similar way, the surface and bed layers provided by the HRCS model can also be converted to a depth-averaged value using the coefficients provided in Appendix B3. It should be noted that current speed reduces rapidly with depth near the sea bed due to frictional drag forces, therefore bottom-deployed devices that extend over a significant proportion of the water column may experience large flow differentials between the top and bottom of a unit.

4.1.1 Tidal Range

The quantification of Mean Spring Range (MSR) and Mean Neap Range (MNR) have been derived from the main lunar (M_2) and solar (S_2) semi-diurnal harmonic constituents of the tide, according to:

$$MSR = 2(M_2 + S_2) \text{ i.e. sun and moon in phase} \quad (1)$$

$$MNR = 2(M_2 - S_2) \text{ i.e. sun and moon out of phase}$$

The Atlas database contains complete quantification of MSR and MNR conditions. Figure 5 presents data for the mean spring tidal range using standard metric units of metres vertical height and with a linear scale from 0 to 8m, in increments of 1m, and with increments of 2m from 8 to 12m. A comparison of this data and the Admiralty 'Co-tidal Chart 5058 British Isles and Adjacent Waters' shows excellent agreement between the two datasets.

This type of data has direct relevance to any marine renewable technology which operates on the principle of converting energy from a rising and falling tide, such as a low head hydro tidal impoundment device.

Standard tidal typology would class the tidal range into the following terms:

Tidal Range (m)	Typology
<2	Micro-tidal
2 to 4	Meso-tidal
4 to 8	Macro-tidal
>8	Mega-tidal

It is expected that mega-tidal range conditions and above are of particular interest to tidal impoundment devices. It can be seen that, from Figure 5, these conditions are restricted to the Irish Sea, outer Bristol Channel, the Wash, the eastern English Channel and the Channel Islands.

An additional tidal parameter included in the Atlas database is the ‘Type of Tide’. A value that gives an indication of the type of tidal regime at a location :

Value (non-dimensional)	Typology
<0.25	Semi-diurnal
0.25 to 1.5	Mixed (mainly semi-diurnal)
1.5 to 3	Mixed (mainly diurnal)
>3	Diurnal

The Type of Tide becomes less reliable when this value exceeds 0.5.

4.1.2 Tidal Flow

Identification of peak tidal flows has been derived for the envelope of spring and neap tidal ranges using the O_1, K_1, M_2 and S_2 harmonic constituents and based upon five ellipse parameters:

- semi-major axis;
- semi-minor axis;
- orientation (clockwise from north);
- phase of the ellipse; and
- rotation direction. (C = clockwise, A = anti-clockwise)

Figure 6 presents details of the peak flow for a mean spring tide, with Figure 7 illustrating comparable data for a mean neap tide. Data is presented using standard metric units of metres/second from near calm (<0.1m/s) to strong flow (>4m/s) conditions. From an observation of these figures it can be seen that higher magnitude currents exist for a larger proportion of the UKCS during the spring tide, with areas of tides >1.75m/s only occurring at a few locations during neaps. These locations are in Yell Sound, in the vicinity of the Channel Islands and Anglesey. Comparative areas under the spring tide occur over a more widespread area.

Previous studies which identify the potentially exploitable tidal flow resource have generally targeted sites providing greater than 1.5 or 2.0m/s on a mean spring tide (DTI 2003, CEC 1996, Triton 2002). This type of data has direct relevance to tidal stream technologies. Such a resource selection is discussed further in Section 6.1.

It is important to recognise that the tidal stream resource can be strongly influenced by rapidly varying bathymetry and coastal topography, with strongest flows commonly found around headlands and through narrow channels (e.g. macro-tidal estuaries and tidal straits). At such constricted sites, where water accelerates past obstructions that are still small in scale relative to the resolution of the source data there may be occasions where the Atlas under-represents peak current speeds.

Additional properties of tidal flow describe the :

- persistence of flows above set thresholds over an annual period; and
- the elliptical form of the rotary flow. This provides detail on the directional properties of the tidal flow, with a flow along a singular axis being represented by a narrow elliptical form and a more rotational flow being shown by a rounded elliptical form.

4.1.3 Annual Tidal Power Estimation

A standard expression to determine the instantaneous theoretical tidal power density (energy flux) available in a tidal stream is given by:

$$P_{cross\text{-}section} = 0.5\, \rho\, A\, U^3 \qquad (2)$$

Where:

$P_{cross\text{-}section}$ = theoretical power density (Watts)
ρ = density of seawater (kg/m^3)
A = cross-sectional area (m^2)
U = instantaneous current speed (m/s)

Hence, the mean power density per unit area of cross-sectional flow (per metre depth) and averaged over a defined tidal period (e.g. neap, spring or annual event) can be expressed as:

$$P_{mean\ power\ density} = 0.5\, \rho\, [\, U^3 \,] \qquad (3)$$

With:

[ ] = chosen averaging period for time series data

Since the tides in UK coastal waters exhibit a distinct spring-neap amplitude variation over successive 15 day periods, in addition to the annual variation, the power density calculation has also been derived separately for peak current of an average spring tide (Figure 8) and neap tide (Figure 9). Units are kW/m^2, with the data presented with a non-linear scale from $<0.1kW/m^2$ to $>2.91kW/m^2$, and with an interval determined at breakpoints through the data. The spatial pattern of spring and neap power is similar to that observed in the distribution of mean current flows over the UKCS.

It is important to note that extractable power will be highly dependent on the physical characteristics of the site and the performance of the energy converter, in addition to the power values presented in the Atlas. The ability to assess a location using any given combination of these parameters is provided in the accompanying GIS resource (Section 6).

4.2 Wave Resource

Variability of the wave resource around the UK, and consequently the amount of wave energy, can be related to:

- the exposure conditions of any site;
- the amount and distance of open water over which the wind blows to generate the waves (the fetch); and
- the strength of the winds generating the waves.

It is generally regarded that the UK is geographically well suited to exploit the wave resource, lying at the eastern end of a long fetch (the Atlantic) which has a prevailing wind blowing from the west. Earlier studies have attempted to quantify the wave resources around the UK and include work previously undertaken for DTI (Whittaker, 1992) and other more recent studies for the EC (Pontes *et al*, 1997). Resource estimates derived by these previous studies were sourced from the Met Office European Wave Model (1/4° latitude and 2/5° longitude) and the WAM model (3° latitude and longitude resolution), respectively, and for a small number of discrete sites in water depths generally greater than 50m.

The rationale in the present study has been to develop a consistency in estimating the wave resource aligned to these previous studies but to use a higher resolution dataset that can provide complete coverage across the UKCS. The data source applied to the Atlas is described in more detail in Section 2.5.

The wave spectrum (i.e. the envelope of wave activity in a sample) characterising the conditions at a given site can be summarised quite accurately by a small number of basic statistical parameters. The most important parameters are:

- significant wave height, Hs;
- wave energy period, Te; and
- mean wave direction of the power flux.

Wave conditions around the UK generally exhibit two components; a locally generated wind-wave (generated across the fetch where the wind has blown), and a swell-wave which propagates into the area from a remote source and characteristically has longer periods. It is important to note that the direction of the swell-wave is not necessarily aligned to the direction of the wind-waves. On such occasions a more precise description of wave spectra can be achieved by inclusion of one standard deviation to each parameter.

For reference, the archive of the UK Waters Wave Model contains hourly records from June 2000 when the model first became operational, with data stored as significant wave height, zero up-crossing period and mean direction for each of wind-sea, swell and resultant wave components. Analysis of the wave data has considered the maximum, minimum and standard deviation values for each parameter. The spatial and temporal scales used to describe the variation in the wave resource are :

- **Annual:** These calculations include adjustment for any seasonal bias inherent in the 3 years and 3 month input data period;

- **Seasonal:** Where the seasons are defined as:
  Winter: December, January, February
  Spring: March, April, May
  Summer: June, July, August
  Autumn: September, October, November; and

- **Monthly:** These calculations provide the range of values for each month.

4.2.1 The Wave Spectrum

Met Office operational wave model spectra are calculated over a domain of 13 frequency (25 to 3 seconds) and 16 directional bins (covering 0 to 360 degrees). Total energy in the spectrum can be represented using a set of simple parameters which describe wave height (energy) and predominant wave periods and direction. Specifically, the parameters maintained in the Met Office archives are:

- H_s Significant wave height (m) $H_s = 4\sqrt{m_0}$ (4)
- T_z Zero-upcrossing period (s) $T_z = \sqrt{\frac{m_0}{m_2}}$ (5)
- D_p Principal wave energy direction (degrees)

where :

m_n = the nth moment of the spectrum

Within the Atlas, these values are assumed to be representative of the entire wave spectrum (i.e. the wave spectra are assumed to be unimodal). In those circumstances where the spectrum describes wind-sea and swell components that are both distinct and significantly energetic this will not be fully correct. However, this remains a necessary compromise for this particular data source and should not impact significantly on the resulting data in its use as an initial decision making tool. For further details see Section 5.

4.2.2 Significant Wave Height

Significant wave height, H_s, is a standard expression that can be used to rapidly identify the variability in wave conditions across the UKCS. Figure 10 presents part of the overall significant wave height data held in the database which describes the (long-term) annual mean wave height. This value has been derived from the whole archive to average out any atypical year of data.

4.2.3 Wave Power Estimation

The quantification of the power transmitted by a wave moving across the sea surface was calculated using methodology similar to that described in Tucker and Pitt (2001) and applied in the Seapower South West study. It is based on the following expression (for more details see Appendix D1):

$$P_w = 0.0623 \rho g H_s^2 c_g \tag{6}$$

where:

- P_w = wave power (W) per metre wave crest
- ρ = water density (kg/m^3)
- g = acceleration due to gravity (m/s)
- H_s = significant wave height (m)
- c_g = wave group speed (m/s)

As previously stated (Section 4.2), the archived wave model statistic for wave period is zero up-crossing period (T_z). This statistic is derived using the spectrum second moment and as a result may be sensitive to high-frequency low energy variations in the wave spectrum. A more generally accepted statistic for wave power calculations is the energy period (T_e) which represents lower frequencies better. This parameter is defined using:

$$T_e = \frac{m_{-1}}{m_0} \tag{7}$$

Whilst T_e is not directly computed by the wave model, an approximation can be made based on T_z. The approximation assumes that a standard JONSWAP spectrum is representative of the average wave conditions over time, in this case the NORSOK (1999) recommended design values for the North Atlantic were applied. T_z and T_e were calculated based on the theoretical spectra for peak periods between 3 and 20 seconds and their ratio determined. The ratio was found to vary between 1.0 and 1.17, with the ratio for a T_z value of approximately 8 to 9 seconds equalling 1.14. This last value was chosen as representative of the best (most) power estimate based on annual mean T_z values for all cases, and, hence for this study, T_e is universally determined across the UKCS using:

$$T_e \approx 1.14 T_z \quad (8)$$

The conversion from these values to annual output in TWh/annum can be achieved by integrating in space and time (e.g. multiply mean power by approx. 12000 metres per Atlas grid box, and 365 days x 24 hours x 60 minutes x 60 seconds). It is important to note that values determined in this manner do not directly provide a realistic quantification of practical output production as the scale of any energy converter and its efficiency rating and consequential downstream energy losses would all need to be considered.

The geographical variation in annual mean wave power is shown in Figure 11. The temporal variation in the wave power is described in the Atlas in terms of monthly, seasonal and annual variation in the mean wave power estimates. It is important to recognise that the annual mean energy yield has strong seasonal biased with peaks during the winter and calms during the summer (Figure 12).

4.2.4 Statistical Analysis of Wave Resource Parameters

To enable a more detailed description of the wave regime a number of standard statistical expressions are provided for H_s, T_z, D_p, T_e, and P_w . Statistical values are contained in the Atlas database for further examination.

The analyses were divided into four components:

- Non-directional wave parameters;
- Exceedance statistics
- Height verses period statistics; and
- Directional wave analyses

These comprise statistics corresponding to those:

- produced in previous studies such as the EU WERATLAS and Seapower South West; and
- summarized in the DTI study carried out by Thorpe (1999).

Each set of statistics was defined not only in terms of annual value (using the three year period from June 2000 to May 2003) but also at seasonal and monthly timescales (using appropriate data from the data base) in order to express important variations in wave climate occurring during an annual cycle. Specifically these can be described as:

- Non-directional wave and power statistics; e.g. mean, standard deviation and maximum values of wave height and power (Table 3). These statistics allow a simple inter-comparison of the bulk differences in wave and wave power climate between sites over the UKCS when visualized in map form.

Table 3. Non-directional wave parameters

Parameter	Mean	Maximum	Minimum	SD (Standard Deviation)
Hs – wave height (m)	Available	Available	Available	Available
Tz – wave period (s)	Available[+]	Available*	Available*	N/A
Power (kW/m)	Available	Available	Available	Available
[+] weighted by wave energy * values associated with maximum/minimum wave height				

- Exceedance statistics. Normalized cumulative frequency statistics that show the proportion of time for which a given wave parameter or power value is exceeded over an annual period (Table 4). These values are useful in assessing the amount of time for which wave conditions fall within a given operating range, and may also be useful for comparison of many sites when visualized in map form. Data bins are chosen to provide an optimal balance between representing the data distribution for the most common values and conserving data volumes.

Table 4. Exceedance statistic intervals

Hs (Wave Height) (m)
>0.5
>1.0
>2.0
>3.0
>4.0
>5.0
>6.0
>8.0
>10.0
>12.0
>15.0

Tz (Wave Period) (s)
>3
>4
>5
>6
>7
>8
>10
>12
>15
>18

Power (kW/m)
>1
>2
>5
>10
>15
>20
>40
>60
>100
>200
>400
>1000

- Wave height versus period scatter tables (Table 5). Normalized frequency tables comparable with those used for wave power calculations in other studies, and useful in assessing the time for which wave height and periods fall within an appropriate operating range. As with the exceedance statistics, the data bins were chosen to provide an optimal balance between representing the data distribution for the most common values and conserving data volumes.

Table 5. Height vs. period scatter tables

	Period (s)								
Hs (m)	<4	<5	<6	<7	<8	<10	<12	<15	>15
<1.0									
<2.0									
<3.0									
<4.0									
<5.0	Frequency values (in % units)								
<6.0									
<8.0									
<10.0									
<15.0									
>15.0									

- Directional wave and power statistics (Table 6). Unless able to be driven from all directions, wave power devices will be dependent upon waves propagating from a prevailing direction. These statistics aim to allow assessment of the degree of 'directionality' in the wave climate at given sites.

Table 6. Directional wave analyses (using an eight direction sectors)

Parameter	Mean	Maximum	Minimum	SD	% Contribution
Hs (m)	Available	Available	N/A	Available	N/A
Power (kW/m)	Available	Available	N/A	N/A	Available

4.3 Offshore Wind Resource

The wind characteristics experienced at a given site can be described quite accurately using a small number of basic statistical parameters. The parameters which have been described within the Atlas, in addition to the associated temporal resolutions, are listed in Table 7.

Table 7. Summary of wind resource parameters

Parameter	Height (ASL)	Temporal Resolution	Data Source
mean wind speed (m/s) (*)	19.5m, 80m & 100m	monthly; seasonal; annual	UK Waters Model & WAsP Model
mean power density (W/m^2 of rotor swept area)	80m & 100m	annual	UK Waters Model & WAsP Model
energy yield (GWh/annum/km^2)	80m & 100m	monthly; seasonal; annual	UK Waters Model & WAsP Model
directions and frequencies (for 11 points for the production of wind roses) (*)		annual	UK Waters Model
Key : (*) refer to Appendix C3.			

As with the wave resource the seasons are classified according to the groups of following months:

- Winter: December, January, February;
- Spring: March, April, May;
- Summer: June, July, August; and
- Autumn: September, October, November.

A total of 7,066 data points were provided by the Met Office, covering time histories in three hourly intervals from 1 June 2000 to 30 September 2003. The required parameters were derived from this substantial volume of data by using the following steps:

- calculate annual mean wind speeds, corrected for the seasonal bias of the data period. This is shown in Figure 13 with the seasonal variation throughout the year shown in Figure 14;

- transform wind speeds to 80m and 100m ASL. The choice of heights was made to reflect future trends in hub heights for offshore wind turbines. A power law relationship was assumed with an exponent of 0.11, which is considered a reasonable approximation for the purposes of the current study; and

- calculate available annual energy yield (AEY) of the wind at 80 and 100m ASL.

4.3.1 Offshore Wind Power Density

Offshore wind power density was calculated using previous methods detailed in the European Wind Atlas, (Troen and Petersen, 1989). It represents the average for the time series at each point and as such gives a value of wind power density of the rotor swept area. This parameter is calculated using:

$$P_{wind} = 0.5.\ \rho\ .V^3 \qquad (9)$$

where:

P_{wind} = offshore wind power density (W/m^2 of rotor swept area)
ρ = air density (1.225 kg/m^3);
V = mean wind speed (m/s)

(N.B. this expression is entirely comparable to the equation used to estimate the tidal stream power density. The fundamental change is the density of the respective fluid from water to air).

Annual average wind power density across the UKCS is shown in Figure 15. A scale from 98 to 1573W/m^2 is applied and with an irregular data interval, again set at break points across the data.

4.3.2 Annual Energy Yield

To estimate the AEY, the power curve of a typical offshore wind turbine and the density of the wind turbine spacing were chosen.

The reference wind turbine used for the conversion from annual wind speed to annual energy yield is taken to be a generic turbine. Its characteristics have been selected by Garrad Hassan to represent the likely configurations of offshore turbines available in around 2010. It has an assumed 5MW rated capacity, 118m rotor diameter and any hub height larger than 80m. An aerodynamic model has been constructed and power curve predicted for this generic turbine. A packing density of one wind turbine per km^2 is also assumed.

The AEY was then derived as a function of annual mean wind speed as follows:

- the wind speed distribution was assumed to be a Rayleigh distribution;
- wind farm losses of 24% were assumed to include: wake losses; downtime; electrical transmission losses; and other incidental losses; and
- a fourth order polynomial was fitted to the resultant function, as shown in Figure 16.

4.4 Resources

The parameters included in the Atlas, as described in earlier sections, can be used to summarize the available resource, for waves, tides and winds, over both the UKCS and within defined sub-areas. An example is given in Table 8a and 8b. In the former the potential available resource over :

- the entire UKCS;
- within territorial waters; and
- outside the territorial waters

is given. In Table 8b, this information is shown for selected water depth ranges of :

- 5 to 30m; and
- 30 to 50m.

Table 8a. Summary of resource availability

Region	Parameter	Resource (If Applicable)		Value
WITHIN TERRITORIAL WATERS	Area (km^2)			16931833
	% total			18.8 %
	Total MW available (annual)	Tidal	(kW/m^2 of vertical water column)	11511
		Wave	(kW/m of wave crest)	19925
		Wind	(W/m^2 of rotor swept area)	17350
OUTSIDE TERRITORIAL WATERS	Area (km^2)			76947820
	% total			81.2 %
	Total MW available (annual)	Tidal	(kW/m^2 of vertical water column)	6916
		Wave	(kW/m of wave crest)	145842
		Wind	(W/m^2 of rotor swept area)	68125
ALL WATERS	Area (km^2)			93879653
	% total			100 %
	Total MW available (annual)	Tidal	(kW/m^2 of vertical water column)	18427
		Wave	(kW/m of wave crest)	165767
		Wind	(W/m^2 of rotor swept area)	85475

Table 8b. Summary of resource availability vs. example depth criteria

Region	Parameter	Resource (If Applicable)		Value	
				5 - 30m	30 - 50m
WITHIN TERRITORIAL WATERS	Area (km^2)			4059613	3091650
	% total			63.5 %	44.8 %
	Total MW available (annual)	Tidal	(kW/m^2 of vertical water column)	4522	3466
		Wave	(kW/m of wave crest)	2364	2934
		Wind	(W/m^2 of rotor swept area)	3406	3113
OUTSIDE TERRITORIAL WATERS	Area (km^2)			2334114	3809988
	% total			36.5 %	55.2 %
	Total MW available (annual)	Tidal	(kW/m^2 of vertical water column)	813	2036
		Wave	(kW/m of wave crest)	1981	3216
		Wind	(W/m^2 of rotor swept area)	2646	4760
ALL WATERS	Area (km^2)			6393727	6879746
	% total			100 %	100 %
	Total MW available (annual)	Tidal	(kW/m^2 of vertical water column)	5335	5502
		Wave	(kW/m of wave crest)	4345	6150
		Wind	(W/m^2 of rotor swept area)	6052	7873

Note that the power value in Tables 8a and 8b are not directly comparable between resources. For example the wave power is per m of wave crest and the tidal power per m^2 of vertical water column. It is recommended that comparisons are made between regions for each resource rather than between resources.

5. Validation of Data Sources

5.1 Introduction

Validation of the data sources used in the Atlas is an important and integral component in maintaining the best available operational system. The validation of the two main data sources, the POL tide model and the Met Office wave and wind models are treated separately in the following sections.

5.2 POL Numerical Schemes

The HRCS model outputs have been compared with 257 coastal and offshore tide gauges and 278 current meter measurements from the British Oceanographic Data Centre (BODC) databank In order to undertake this, the model tidal parameters were interpolated to the exact longitude, latitude and depth of the observation selected. The parameters of tidal elevation and currents have been assessed and are discussed in Appendix B4. In summary :

- there is overall good agreement between observed and computed tidal elevations over the UKCS; and

- the model is, in general, in good agreement with the observations of most tidal components. The spread, which in general increases with current speed, shows the variability due to bathymetry which might be expected within a grid cell. This indicates the care which should be exercised when comparing observed data with model data.

In addition to comparing the HRCS model output with observation data, comparisons have also been made with the CS3 model output and the output provided within the Seapower South West study. A good correlation can be observed within these data sets, and in summary:

- areas of flow speed hot spots (i.e. around headlands) and low spots (i.e. middle of the North Sea) are observed in similar locations over the UKCS;

- the areas of higher current speeds are larger and of greater magnitude from the HRCS surface output as compared to the CS3 output as the latter represents a depth-averaged current speed whilst the former represents the surface layer in the water column where current speeds are typically highest within the entire water column; and

- the HRCS provides an improved, higher resolution of data than both the CS3 and Seapower South West models

These points are discussed further in Appendix B4.

5.3 Met Office Numerical Schemes

5.3.1 Wave Model Data

Ordinarily validation procedures focus upon forecast performance and skill at various lead times using indices set up to determine these factors over an entire model domain. In the context of the Atlas database however, the data validation requirements are different as the source data used is from a model hindcast or very short forecast lead time, i.e. forecast skill should not be an issue. Therefore, the main issues to be addressed are:

- over the defined climate period, does the distribution of wave model data represent the actual spread of wind and sea-state conditions well?;
- does the sourced data broadly represent long-term variations in wave climate?; and
- why is the performance of the sourced model data better or worse for specific regions of the UKCS?

Observation time-series data were selected from sites comprising the Met Office Marine Automatic Weather Station (MAWS) Network (Figure 17) in order to undertake the validation exercise. These sites provide direct observations of both marine wind and wave parameters, specifically wind speed (at 10m above sea-level), wind direction, significant wave height and wave period. Locations were chosen to provide a spread of representative sites around the UKCS and in as many SEA areas as possible, and are summarized in Table D2.1.

To determine whether the sourced data represented long term variations in the wave climate over the UKCS, the archive of Met Office European Wave Model data was utilised. This data source extends over 12 years.

Comparisons were made between H_S values for each data type (UK Waters, European, observed) as an indicator of model behaviour. Specifically seasonal and annual averages were compared to judge the overall performance of each data type, whilst seasonal H_S average time-series and H_S distributions were used to examine any longer term effects (European data) that might be missed by the relatively shorter (UK Waters and observed data) time-series. For details of the comparison and a detailed discussion of the results obtained, the reader is referred to Appendix D2.

The use of the UK Waters Model climate dataset and long term experience in running the Met Office wave models operationally means, generally, that these data should be considered as a reliable qualitative resource for comparing both wind and wave power resource over the UKCS regions. The minor shortcomings of using this data has been given in Section 2. The ability of such a short term dataset to fully represent the wave climatology at any given location will depend on exposure to individual storm conditions, both in terms of geographical location and the season examined.

For summer and the least exposed regions of coastline the number of storm events experienced will be fewer than in winter months at the most exposed sites. As a result the probability of obtaining a near complete range of possible wave conditions over a short period will be smallest at sheltered sites. For the data presented here, it is suggested that the full range of seasonal variations in significant wave height may not be incorporated into the Atlas climatology in the most sheltered areas (e.g. English Channel). Conversely, in areas directly exposed to wave energy (e.g. Northwest Approaches) the time-series used is likely to be very similarly populated in terms of differing wave conditions compared to the long term climate. As a result, the wave resource climate is liable to be best represented in the Atlas for regions where the wave resource is most energetic and consistent.

Importantly for the intended purpose of the Atlas, in terms of the climate averages for both annual and seasonal time periods, the three-year dataset generally falls within ±15% of the longer term average. On this basis, whilst the recommendation for any site specific study of wave resource is that a long term dataset be considered in addition to that presented here, for the decision making purposes the Atlas is intended for, the time-series used can be taken as providing acceptable estimates of wave climate in addition to being the best available resource in terms of spatial coverage. Any effects derived from the North Atlantic Oscillation (NAO) are also discussed in Appendix D2.

The following points should be noted when using the Atlas data:

- For open sea sites, Atlas wave data is reliable, but it is useful to consider whether the region is likely to regularly include a significant swell component in its sea-state (e.g. Atlantic facing regions). In these cases wave power may be underestimated and wave direction data should be checked with regard to prevailing swell directions.

- In coastal zones, wind resource data should be compared with local understanding of prevailing wind conditions and topographic features given due consideration. Wave resource data should be compared with bathymetric charts to gain an understanding of likely local wave refraction and sheltering effects as waves travel into shallower locations. An appreciation of the general wind-sea versus swell climate should also be gained where appropriate.

5.3.1.1 Comparison with Seapower South West

During the Seapower South West study, a similar determination of T_e from T_z was derived through an analysis of actual (1-Dimensional) wave spectra generated by the Met Office wave models through the winter period of 2001 to 2002. It was concluded that the relationship between these parameters is :

$$T_e = 1.1625T_z + 0.3285 \qquad (10)$$

The differing values of T_e used contributed to a difference between the average power at selected sites in i) the Seapower South West study; and ii) the Atlas. The average power was approximately 5 to 10% higher in the Seapower South West study (Pitt, 2004, *pers. comm.*). Following discussions between both projects this difference was felt to be a generally acceptable error. Use of the JONSWAP derived T_e to T_z ratio continued within the Atlas project as it is slightly more generic and therefore more applicable across the whole UKCS, including those areas where the wave climate differs significantly in terms of swell and windsea contribution to the south west region.

Whilst the Seapower South West study provides a wave resource assessment for the south west of England, this has been based upon non-directional frequency tables of wave height against wave period at only eleven sites within this region. The Atlas resource uses original Met Office input data that covers this entire area. Thus the Atlas provides a more refined wave resource assessment in terms of greater level of detail, by spatial scale and directional parameters.

Selected parameters derived for the Atlas study can also be compared to the 'Wave Climate of the British Isles' (DTI,1991) where it is clear that there is agreement between the distribution and range of wave heights from the two studies.

5.3.2 Wind Data

The wind data derived from the Met Office numerical models has been validated against other sources using three methods. The first uses expert knowledge of the wind climate over the UKCS, the second uses a data set which exists for the coastal region (where coastal is less than 30km offshore), whilst the third uses a long-term data set that covers the entire UKCS.

Observations on the model output highlighted some unexpected mean wind parameters occurring to the north-west of Scotland (Figure 13). Although of academic interest, this is not considered to be of any practical significance for the Atlas. These were reviewed by the Met Office and two possible explanations proposed :

- the result is physical. Storm tracks approaching from southwest to northeast and tracking north of Scotland, then tend to 'stick' as they pass between UK and Iceland and flanked to the east by Norway. Thus leading to an average storm centre at the low wind speed spot at approximately 60^{o}N, 10^{o}W; and

- the low wind speeds in what is in effect the north-western boundary area of the UK Waters Model may be a result of the numerical scheme used at the Global Model /UK Waters Model boundary, i.e. it is a model artefact.

5.3.2.1 The coastal zone

When the UK Waters Model wind speed was compared with existing data held by Garrad Hassan, it became clear that the former was typically higher. The average difference was 2m/s, with a maximum of 4m/s. This difference decreased dramatically with distance offshore (as indicated in Appendix C4). Thus data has been provided for the entire coastal area, defined as less than 30km offshore, using WAsP modelling techniques.

5.3.2.2 Long-term data sets

Long-term data from the European Waters Model were provided for 21 points distributed around the UK coast for comparison with the UK Waters Model short-term data. Data extracted from the model cover a period of approximately 12.6 years from 1991 to 2004. A similar verification analysis was performed by the Met Office for 9 available wave buoy and lightship positions (described in Section 5.3.1 and Appendix D2). The name and coordinates of the wave buoy and lightship positions are given in Table 9, which also provides the coordinates of the closest UK Waters point for each European point.

Table 9. Location of sites used to compare the UK Waters Model and the European Waters Model

Site Name	Closest UK Waters Point (deg WGS84)		Closest European Point (deg WGS84)	
	latitude	longitude	latitude	longitude
K5	59.06^{o}N	11.42^{o}W	59.00^{o}N	11.26^{o}W
RARH	56.94^{o}N	09.92^{o}W	57.00^{o}N	10.06^{o}W
Seven Stones	50.06^{o}N	06.08^{o}W	50.00^{o}N	06.06^{o}W
Turbot Bank	51.61^{o}N	05.08^{o}W	51.50^{o}N	05.26^{o}W
Lyme Bay	50.61^{o}N	02.75^{o}W	50.50^{o}N	02.86^{o}W
Greenwich	50.39^{o}N	00.08^{o}W	50.50^{o}N	00.06^{o}W
Aberporth	52.28^{o}N	04.58^{o}W	52.25^{o}N	04.46^{o}W
K17	55.39^{o}N	01.09^{o}E	55.50^{o}N	01.14^{o}E
K16	56.94^{o}N	00.08^{o}W	57.00^{o}N	00.06^{o}W

Wind speeds were compared at these locations and the ratio of short-term to long-term annual wind speed (windiness) for each point was calculated. The comparison revealed slight differences in the two datasets, with the largest changes being located at the Lyme Bay and landward to the K17 stations (Appendix C3; Figure C4.3). It is suggested that these changes exist as per the wave data differences (see Section 5.3.1). Full details of this validation procedure are given in Appendix C4. It was therefore concluded that the data used within the Atlas represents the best available information at the time of the study.

6. Spatial Database

The marine resource parameters held within the Atlas database can be viewed as 'maps', similar to pages in a book. However, when considering the division of the UKCS to certain technologies / rounds of development, it is also important that decision makers, such as DTI, are able to interrogate the resource using the attributes of the various technologies. For example, there are six potential variants of tidal devices alone as shown in Table 10. In order to evaluate the potential of the different devices, it is necessary to be able to combine a number of mapped parameters to generate maps that reflect the relative placing of these devices.

Table 10. Examples of the types of tidal flow energy converters presently available

Rotor Type	Installation Type
axial flow	surface mid-depth bottom
cross-flow	surface mid-depth bottom

The attributes of existing technologies have been collated through an industry consultation exercise (see Section 6.1) and used to develop a GIS based system which allows the

- interrogation of the tide, wave and offshore wind resource; and
- assessment of the generating potential from the three marine resources.

In order to allow these functions to be undertaken, the tide, wave and offshore wind parameters have been incorporated into a structured database, which is accessible via a GIS system, as summarised in Figure 18; Appendix E1. This system is intended for use on an ArcGIS 8.3 platform. The features of the system are described in the following sections.

6.1 Resource Assessment

The Atlas has been developed to allow the regional assessment of marine resources for use as a support tool within the SEA process. The parts of the GIS system that form this section (with reference to Figure 18) are the :

- Criteria Selector;
- Graph Manager; and
- Resource Reporter.

Information has been collated on both presently available technology (energy converters) as well as future technologies being funded under the DTI New and Renewable Energy Programme. This information-gathering exercise was facilitated through industry consultation involving both telephone and email discussions. The primary details collated relate to the generic properties of the relevant technologies that are being developed, for example idealised deployment conditions and predicted energy conversion efficiencies. The full list of questions are given in Appendix E2. The GIS system developed incorporates features of the questionnaire to allow the interrogation of the tide, wave and wind resource parameters. The interactive interrogation of this database is undertaken through the definition of certain parameters by the user, which are then used to identify those areas which comply with the definition.

6.1.1 Resource Assessment Using the Criteria Selector

The information contained within the Atlas can be interrogated in a number of ways, as listed in the User Manual which accompanies the database. This section introduces the main functionality of the database through some worked examples of the resource assessment.

Prior to an assessment of a resource, it is important that any other environmental constraints are taken into consideration. An example of this would be water depth. This constraint is important to different technologies for various reasons, for example the nature of the wave resource is depth-dependant with those waves in shallower water being more susceptible to breaking. Another example can be given for the tidal resource where deeper water may be advantageous as the greatest currents exist in the upper 50 to 60% of the water column, thus in deeper water this will extend over a greater depth range than in shallower water. The bathymetric information held within the Atlas can therefore been interrogated to select areas where depths which are between a user specified range. For this example a range of 40 and 150m has been selected, as shown in Figure 19. This range was chosen based on the full list of responses given in the marine energy industry consultation.

The selected depth range can be interrogated further through the request for a selection of a pre-defined range of, for example tidal power. As an example, the depths selected in Figure 19 have also been interrogated with respect to the wave resource. Here, those locations in the depth range 40 to 150m whose wave power is within the range 10 to 20kW/m have been selected, as shown in Figure 20. It can be observed that these wave powers are restricted to the north North Sea, south-west and the north-west.

The tidal resource has also been interrogated to highlight those areas where the spring current speed is greater than 2.0m/s. This is shown in Figure 21. It can be observed from this plot, that this range of tidal speeds is confined to localised areas, in particular around headlands and in narrow straits. This plot also highlights the importance of providing the tidal parameters to such a high resolution as provided in the Atlas due to the need to resolve the resource within such areas.

Figure 22 and 23 illustrate an interrogation on the wind resource in water depths less than 25m and 50m, respectively. The wind power is therefore shown for locations within the coastal zone and in the southern North Sea.

The GIS functionality is such that more than one resource parameter can be interrogated at once rather than the two steps described in the previous examples, thus allowing various scenarios to be developed. An additional ability within the database is to save all interrogation criteria and results in order to reduce computational time and repeats during latter stages of interrogation. The details of the system are given in Appendix E1 with details on how to use the system provided in the user guide supplied with the GIS system.

It is clear from a comparison of Figures 20 to 23 that, as previously mentioned, the tidal resource is more spatially confined than the wave, and wind, which are more spatially consistent.

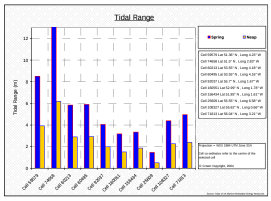
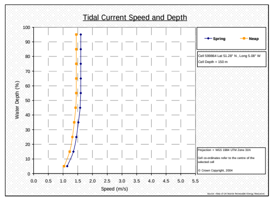
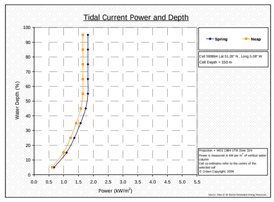
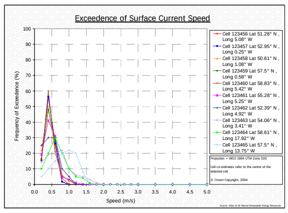
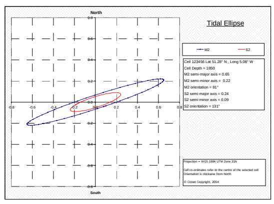
Responses from the industry questionnaire have been included within the Technology Reporter section of the GIS. These provide the user with further assistance on those considerations, i.e. factors which constrain the depth of deployment of a device, that should be made prior to deciding on a future site for development. Such considerations include those of array spacing which would allow further clarification on the number of devices which could be installed in any one area against the amount of power available.

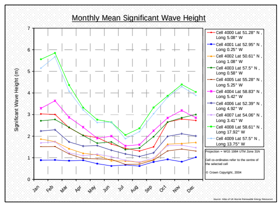
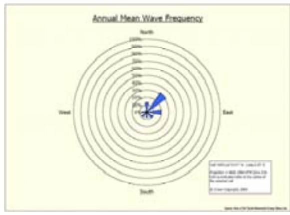
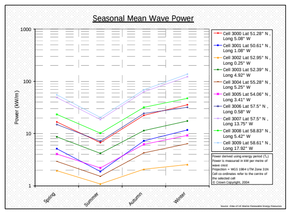
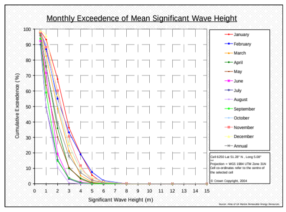
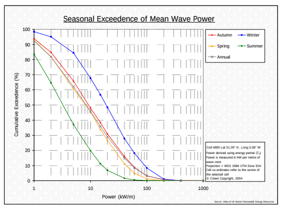
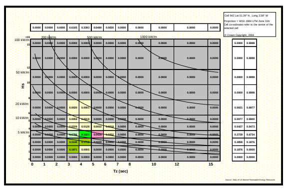
6.1.2 Resource Assessment Using the Graph Manager

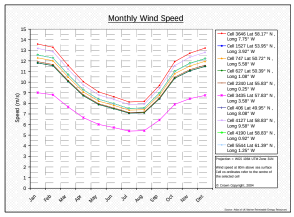
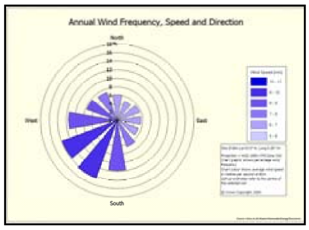
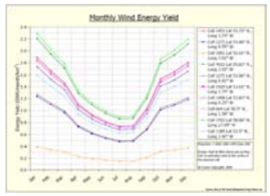
Each of the cells held within the resource database can be interrogated to show and compare tide, wave and offshore wind parameters using a bespoke facility in the GIS called the Graph Manager. This enables the user to visualise wind, wave and tidal resource parameters which cannot be conveyed easily using conventional two-dimensional thematic mapping. Selected parameters are illustrated in a graphical form which can be exported from the GIS system to allow incorporation into a data summary report. The graph options included are listed in Table 11. All parameters provided in the Atlas are listed in Appendix E3.

For those parameters unsuitable for presentation in a graphical form, the GIS interface will display it in tabular form as either a value or coloured cell. An example of this is given in Figure 10 which illustrates the wave heights over the UKCS.

Table 11. Graphical presentation of resource assessment

Energy Resource	Parameter / Graph	Description	Example
Tidal	Range	Tidal range is shown for both the spring and neap tides for a maximum of ten locations per graph. The presentation of the data in a bar chart format clearly allows comparison between sites, as shown in the example here.	
	Current speed	Current speed for spring and neap tides are shown at 10% depth intervals throughout the water column. These are calculated from the numerical model surface speed output using the scaling values given in Appendix B3. One site is shown per graph. In this example it can be seen that the velocity profile through the water column is similar on the spring and neap tide, with the greatest current speed for both predicted in the upper 50% of the water column.	
	Current power	Current power for spring and neap tides are shown at 10% depth intervals throughout the water column. These are calculated from the numerical model surface power output using the scaling values given in Appendix B3. One site is shown per graph. In this example it can be seen that the velocity profile through the water column is similar on the spring and neap tide, with the greatest current power for both predicted in the upper 50% of the water column.	
	Current speed exceedance at surface	Frequency of occurrence of the average annual current speed . These are shown is shown for a maximum of ten locations per graph. In this example, the most frequent occurrence is at the lower speeds.	
	Tidal ellipse	Tidal ellipses are presented for the M_2 and S_2 components of the tide (see Appendix B3). One location per graph is shown. The peak spring tidal velocity can be determined from the ellipses from the addition of the M_2 and S_2. The orientation of these components is also given and in this example the tide flows along a north-east: south-west axis.	

Energy Resource	Parameter / Graph	Description	Example
Wave	Wave height	Significant wave height can be presented in both monthly and seasonal graphs for a maximum of ten locations per graph. In this example it can be seen that the wave heights at all locations are greatest in February and smallest in July.	
	Wave frequency	Wave frequency is presented for annual and seasonal periods for a total of eight sectors, each representing 45 degrees. Only one location is shown per graph. In this example, the dominant wave frequency is the north-east sector.	
	Wave power	Wave power is presented both monthly and seasonally for a maximum of ten locations per graph. In this example it can be seen that the wave power at all locations is greatest in February and smallest in July.	
	Wave height exceedance	Wave height exceedance is presented for monthly, seasonal and annual periods. This is shown for a maximum of one location per graph. In this example, the height distribution can be seen to be contained between that in February and August.	
	Wave power exceedance	Wave power exceedance is presented for monthly, seasonal and annual periods. This is shown for a maximum of one location per graph. In this example, the power distribution can be seen to be similar for a) spring and summer; and b) autumn and winter.	
	Wave power, described in ranges of Hs and Tz	Wave power is also displayed as a function of Hs and Tz. Bands are shown illustrating the power available for a combined range of these parameters. Occurrences of various combinations at one site are shown as counts and coloured with red representing high counts and blue low counts.	

Energy Resource	Parameter / Graph	Description	Example
Wind	Wind speed	Wind speed is presented both monthly and seasonally for a maximum of ten locations per graph. In this example it can be seen that the wind speeds at all locations are greatest in the winter months and smallest in the summer months.	
	Wind direction	Annual wind frequency, speed and direction is provided for eleven locations within the UKCS. In this example, the greatest wind speed comes from the westerly to southerly sector.	
	Wind energy yield	Wind energy yield is presented both monthly and seasonally for a maximum of ten locations per graph. In this example it can be seen that the values at all locations are greatest in the winter months and smallest in the summer months.	

6.1.3 Resource Assessment Using the Resource Reporter

One of the key advantages of storing all of the data in GIS is that it facilitates the interactive comparison and analysis of the parameters from the different resources. The Resource Reporter tool :

- allows the user to select areas for further resource analysis, generating a report which lists the physical attributes, such as depth range and distance from the land, of the selected area;

- automatically determines those cells within the user defined area which are suitable for technology deployment. This sub-selection is undertaken using criteria which have been defined in the industry questionnaire and is calculated separately for the three resources; and

- automatically calculates the raw resource and power statistics for the sub-selection. At this stage the efficiency range of the technologies, which was obtained from the industry questionnaire, are applied to generate an estimated power output range for each resource.

The results calculated within the Resource Reporter are given in units that are resource specific, for example wave power is given in kW/m of wave crest and tidal power in kW/m^2 of vertical water column. It would therefore be desirable to report the resource potential in a directly comparable unit, for example annual energy yield. This calculation was undertaken for the wind resource due to the ability to define a wind device with generic characteristics i.e. rotor diameter. However, both wave and tidal devices are not yet as established nor as generic as the wind technologies. This can be seen using the characteristics of Pelamis and Wave Dragon (wave devices) and MCT and Stingray (tidal devices). Thus, whilst it would be possible to undertake this calculation for specific wave and tidal technologies, present confidentially agreements presently restrict this.

7. Future Work

The present Atlas uses the best available data sources to derive an estimate of the marine energy resources over the UKCS. These resource estimates have been tested against the present technology under development to consider potential energy yields. However, it is fully understood that both the data sources and technologies will advance over the coming years.

An example of the improved data source which has already been encompassed into this study is the development of the POL HRCS model. Indeed, Section 6 illustrates how important the inclusion of this new model data has been, resolving more accurately the flows around headlands and in narrow straits. Therefore as the state of the wave modelling improves in coastal regions, it is important that the resultant information be included in the Atlas database.

It is understood that technology will advance, as seen in the wind industry which is the most developed of all marine resource technologies. This is also true for wave and tidal technologies, in particular for tidal where there is a lower state of technology advancement than for the wave technologies (*pers. comm*. Fraenkel). This can be illustrated with the growth of wind turbine machine size which started at, approximately, 50kW, developing to a plateau of 400 to 500kW in the mid 90's. The turbine size then grew rapidly to reach the present commercial size of 1 to 2MW. The design of these turbines is still undergoing development with some manufacturers (examples are Nordex, RePower, Vestas and Enercon) presently designing 5MW, 118m diameter, turbines. It therefore seems reasonable to assume that the current average size of wind technologies will continue to increase with time. Indeed, it is expected that there will be further size increases, and manufacturers are today offering machines on the market in excess of 3 MW (Table 12).

Table 12. The main offshore turbine manufacturers

Manufacturer	Rotor Diameter (m)	Rated Power (kW)
NEG Micon NM92	92	2750
Bonus	107	3600
Nordex N90 / 2.3MW	90	2300
GEWE	104	3600
Enercon E112	114	4500
DeWind D8	80	2000
RePower	126	5000
Vestas V90	90	3000
Others	90 to 110	3000 to 4200

Whilst the development of technologies continues, it should be noted that there are likely to be practical, engineering and cost limitations on size.

Therefore, whilst the Atlas will prove invaluable in decisions on future developments over the UKCS, its usefulness can be extended further by the regular maintenance of the database, as can be easily offered by the current project team due to their familiarity not only with the GIS system but also the data sources.

In summary, the ways in which this can be undertaken can be classed into maintenance and development services. These are given below:

- Maintenance
  - validation of the database through the use of measurements collected, and made available, after the production of this database. As more areas are considered for the development of marine technologies, a larger database of site-specific measurements should become available. It would be of great value if these were able to supplement current data held in the Atlas;
  - addition of new data to the wind and wave archive. The data used here is sourced from a three and a third year archive and as time commences then this archive will be updated. The inclusion of this data would act to update the Atlas and provide a more complete range of seasonal variations (as described in Section 5); and
  - amend the constraints and assumptions applied in the GIS to include information from new or updated technologies.
- Development
  - addition of more layers to the GIS interface. Examples would be seabed geology and Marine Special Areas of Conservation (SAC);

- introduction of data from new sources, this has been undertaken during this project as the inclusion of the new POL HRCS model. An example would be, as previously stated, to use techniques which improves upon the present state of coastal modelling;

- input from other initiatives. This includes the results from the Supergen Marine Consortium who are currently investigating the limitations of energy extraction from tidal currents (for further information see: http://www.rgu.ac.uk/cree/general/page.cfm?pge=10782);

- enhance the functionality of the GIS tools to report a directly comparable energy yield value for all of the resources following the further development of the wave and tidal technologies, and

- include specific information into the GIS system regarding specific wave and tidal technologies following the revision of present confidently agreements.

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